Human-Robot Collaboration in Automotive Industry

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Human-Robot Collaboration in Automotive Industry

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Sahar Heydaryan

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Summary

Human–Robot Collaboration is a new trend in the field of industrial and service. Application of human-robot-collaboration techniques in automotive industries has many advantages on productivity, production quality and workers' ergonomic; however, workers' safety aspects play the vital role during this collaboration. Previously, the machine is allowed to be at automatic work only if operators are out of its workspace but today collaborative robots provide the opportunity to establish the human robot cooperation. In this thesis, efforts have been made to present innovative solutions for using human-robot collaboration to develop a manufacturing cell. These solutions are not only used to facilitate the operator working with collaborative robots but also consider the worker safety and ergonomic. After proposing different solutions for improving the safety of operations during the collaboration with industrial robots, the efficiency of the solutions is tested in both laboratory and virtual environments. In this research, firstly, Analytic Hierarchy Process (AHP) has been used as a potential decision maker to prove the efficiency of human-robot collaboration system over the manual one. In the second step, detailed task decomposition has been done using Hierarchical Task Analysis (HTA) to allocate operational tasks to human and robot reducing the chance of duty interference. In the International Organization of Standardization's technical specification 15066 on collaborative robot safety four methodologies have been proposed to reduce the risk of injury in the work area. The four methods implied in ISO/TS 15066 are safety-rated monitored stop (SMS), hand-guided (HG), speed and separation monitoring (SSM) and power force limiting (PFL). SMS method reduces the risk of operator's injury by stopping the robot motion whenever the operator is in the collaborative workspace. HG method reduces the chance of operator's injury by providing the possibility of having control over the robot motion at all times in the workstation using emergency system or enabling device. The SSM method determines the minimum protective distance between a robot and an operator in the collaborative workspace, below which the robot will stop any kind of motion and PFL method reduces the

momentum of a robot in a way that contact between an operator and the robot will not cause any injury. After determining the requirements and specifications of hybrid assembly cell, few of the above-mentioned methods for evaluating the safety of human-robot-collaboration procedure have been tasted in the laboratory environment. Due to the lack of safety camera (sensors) in the laboratory workstation, the ISO methods such as SSM, that needs sensors in the workstation, have been modeled in virtual environment to evaluate different scenario of human-robot-interaction and feasibility of the assembly process. Implementing different scenarios of ISO methods in hybrid assembly workstation not only improves the operator safety who is in interaction with the collaborative robot but also improves the worker ergonomic during the performing of repetitive heavy tasks.

Acknowledgment

I would like to acknowledge my Ph.D. supervisor Professor Giovanni Belingardi for his support, guidance, advice and insight throughout the research.

I would like to dedicate this thesis to my loving parents (Houshang & Hamideh) and my forever love Soroosh

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Chapter 1

Introduction

1.1. Background

Nowadays, one possible solution for industrial workers whose tasks are characterized by non-ergonomic duties may be replaced by industrial robots. These duties mainly consists of operations with heavy loading, painful or rough positioning of objects with respect to the worker or dangerous tasks such as working with toxic or hot objects.

The noticeable characteristics of robots are to be able to perform repetitive tasks which need high accuracy to fulfill goals; they are also fast and tough enough, in comparison with humans, to make it possible to speed up their duties completeness with better quality and cheaper cost. Now this question rise up: why should we keep along the production lines humans which can produce errors? The answer is that some duties need operators able to think but robots are not capable of thinking, they just execute commands and accomplish pre-learned movements. In other words, robots are designed with six or seven degrees of freedom and they are limited by their determined programming, while humans are more flexible, for example the upper limb of human body has thirty degrees of freedom. A lot of challenges and barriers have still remained in both fully-manual and fully-automated operations. Human-robot cooperative techniques are trying to break these barriers by utilizing of personnel together with robots in challenging applications [1].Whenever all tasks are performed by human operators in production line, the working efficiency and productivity are important issues. On the other hand, many solutions have been proposed to assist the human operator in working place; one of these proposed solutions is to use the robotic technology for increasing the efficiency of the production line [2-4]. One of the benefits of human- robot collaboration is to provide more flexibility for the operator in order to facilitate his tasks performance with less payload objects. This collaboration would be similar as in the case of assistance of one operator by another operator. This kind of cooperation can develop the work efficiency by semi-automatizing some parts of the operation so that the operator can focus more on his tasks which require more human skill. However, this collaboration may be extremely dangerous due to possible unpredictable, wrong motion of the robot which can cause irreversible injuries to the operators [5]. Generally, manufacturing assembly process can be divided into two different categories. In the first category, there are many assembly steps where to use robots for performing efficient tasks, to lift objects while respecting rules and standards. Due to the development of industrial robots during these last decades, they can autonomously perform their jobs to assemble simple products. The second category needs human skills since industrial robots cannot perform the tasks perfectly just by themselves. In order to complete this classification, in between the mentioned two categories, however within the second category case, a new solution that intend to integrate the advantages of both human and robot can be devised; this solution is called Human-Robot Collaboration (HRC) technique [6, 7]. However, these types of jobs cannot properly be controlled or done just by robots like wiring harnesses, seals, limp components [8] .Collaborative robots are also called "cobots", robotic assistants or cooperative robots. The cooperative robots are designed for collaboration with human, they don't need severely different design from standard industrial robots which are commonly used in conventional factories when they are already matching with safety standard ISO EN 10218. Though the robots should be equipped with other safety components; however, Collaborative robots and other outlying devices that are aimed to improve the safety of robotic workplaces are not designed to fully substitute current technologies. A new technical specification ISO/TS 15066 (Robots and robotic devices – Collaborative robots) has been defined and published on February 2016 for collaborative robots. Assistant robots widen the portfolio of robotic applications in the industry and they bring several crucial advantages. From the point of view of production costs, since company administrative officers have to take into account the worker salary, the demand of collaborative robots usage is different from country to country. In developed countries there is a high competition between companies to produce collaborative robots in comparison with countries with very cheap labor salaries. There is a relationship between the labor economics and the burden which he is imposed by; due to this reason, an improvement of the working environment can lead to a decrease of laborers' injuries.

1.2. Safety of collaborative robots

Collaboration between human and robot in share working area when the robot moving with high speed needs to deal with safety issues. According to international standards, if the robot moves objects with weight up to several tons or moves pieces with acceleration up to 10g, it should be sufficiently secured and kept away from the operator by a fence and colored by warning icons. Whenever the robot operational area is intruded, the robot should stop immediately to prevent collision, harm or fatal injury. In order to use human-robot collaboration in production line, it is necessary to optimize few parameters such as payloads and velocity of robots. The load capacity of collaborative robot is typically around 10 kg and the maximal velocity of motion is typically limited to 250 mm/s . To meet this situation, it is needed to design light-weight robots that may cause no serious injuries to operator in case of impact and collision. However these limitations are not sufficient to prevent the collision completely and the robot should be secured further by using detecting sensors or other collision avoidance methods.

1.3. Problem statement

In automotive industries many tasks are done by humans which may have irreversible effects on human health in case ergonomic issues are not properly considered during the work place design, but by bringing robots in addition to the human along the production lines, thus by applying human-robot collaboration method, could result in a relevant decrement of the ergonomics problems. This is clearly a critical decision. This decision asks for many attentions to be paid, including detection of the minimum requirements, rules and requisites for cooperation of humans and robots in a collaborative environment and setup of the list of constrains and apply the relative reference cases. Also, in order to achieve innovative workplace needs to identify a specific target with related appropriate requirements.

1.4. Aims and objectives

In this research activity, after having made a summary of the methodologies typically applied in the development of this particular study, efforts have been made to develop a complete analysis of manufacturing processes that have been designed to exploit the advantages of using human-robot cooperation. The developed analysis takes into consideration different aspects of operator´s safety and ergonomic issues. Different standards for collaborative robots have been considered to reduce chance of the operator´s injury in the workstation. The implementation of ISO standards both in laboratory and virtual environments for simulating, visualizing, evaluating and optimization of human robot collaborations not only resulted in an improvement of the safety of worker but also of the ergonomic of the operator during the assembly process.

This objective is met through addressing the following research questions:

RQ1: How can be performed simulation, visualization and evaluation of human-robot collaboration workstations with respect to the ISO standards and constrains?

RQ2: How can human-robot collaborative workstations be optimized?

RQ3: How can simulation, visualization, evaluation and optimization of human-robot collaboration be applied in design of real and laboratory workstation?

1.5. Overview of the thesis

Chapter I presents the different concepts of human-robot interaction levels and discusses the problems and objectives of this research.

In Chapter II various aspects of human-robot collaboration, which are presented on related work in the literature, will be reviewed. In the first part of chapter II, hazards related to the robots are identified then standard techniques regarding to each interaction levels are discussed for decreasing the chance of dangerous accidents. In the next section, up to date strategies for approximating and refining safety at the designing and planning stages are considered.

Chapter III reviews the specific topics which are related to decision making methods and task analysis. These methods were selected after deeply studying and reviewing of different methods in published papers.

In Chapter IV, the overall methodology of the thesis is presented. It is a combination of knowledge-based requirements including rules and standards in robotic safety and ergonomics which are applicable for human-robot interaction domain. The first part of this methodology is based on decision making approach to introduce advantage and disadvantage of robot collaboration application beside human during complete tasks. Then decision makers apply Analytic Hierarchy Process (AHP) method to decide whether applying robot beside human or ignore it.

In the next phase, tasks interaction levels are described. Then the Hierarchical Task Analysis (HTA) method is applied according to capability of human and robot to assign duties during complete tasks. At the next step, virtual environment modeling of the assembly process is described. Further, basic procedures of simulation including preparation of model parts, domains and standards of robot safety requirements are explained. At the last step, different case studies are run in the real laboratory environment to test different scenario of collaborative tasks.

In Chapter V, the feasibility of human-robot collaboration is investigated for a case study in experimental and simulation scenarios with respect to ISO Technical Specification (TS) 15066 for safety-rated monitored stop (SMS) and hand-guided method (HG). In the first step, the AHP method as a decision-making method for the human-robot collaboration system is applied to prove the general advantage of the human-robot collaboration over the manual assembly solution. Different criteria are considered for the comparison of the possible different solutions while applying the AHP method. Using the HTA method, the hierarichal algorithm for allocating the collaborative tasks to operators and robots is constituted. In the third step, the assembly process is simulated using the Tecnomatix Process Simulate virtual environment software to test the effectiveness of the HTA method in the case of task allocation. Finally, the feasibility of the design is tested using the laboratory environment and defects are recorded.

In Chapter VI, the analysis to determine the minimum separation distance between human and robot in a collaborative workspace for the same case study is developed. Using operational speed and worker-robot separation monitoring methodology (SSM) as one of the available method to reduce the risk of injury based on the ISO technical specification 15066 for collaborative robot the framework of methodology is designed. Virtual environment simulation is used to determine the SSM algorithm parameters for estimating the minimum protective distance between the robot and operator. Using ISO/TS 15066 and virtual environment simulation, the minimum separation distance between operator and robot is been estimated. In chapter VII, the overview of the conclusions and findings through the research will be presented once again.

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Chapter 2

Literature Review – Safety for Human-Robot collaboration

2.1. Introduction

There is an increasing trend to apply industrial robots in manufacturing industries, specifically on the assembly lines, due to their superior performance and easy instruction learning ability of robots. Although there are still significant challenges which remain unsolved in applying automated assembly lines, the automotive, airplane and electronic industries have already been automated up to more than fifty percent [1-3].

One of the most important challenges for manufacturing industries in the developed countries is the increased global competition [4-5]. This puts higher requests on productivity developments to face with the products coming from rising markets. This productivity improvement should be made at the level of the entire companies, furthermore effective and efficient business methodologies to well-designed production systems and preparation frameworks. In order to tackle with this challenge, industries decide to explore the possible collaboration of robots and human operators to improve safety, ergonomic, quality and productivity in manufacturing assembly lines such systems are named Human-Robot Collaboration (HRC). In this system robot and human share workspace and collaborate toward a common goal. Industrial robot is defined as a controlled automatic machine, which can be either mobile or fixed in place for use in the industrial automation applications, programmable for three or more axes, in case of multipurpose applications the manipulator is reprogrammable [6]. The advantage of collaboration between industrial robots and humans are achieved by combining them in an innovative collaborative production system based on desired individual characteristics. The preferred desired characteristics of robots are staying in work power and repeatability, changeability in operation speed, and for human are staying in flexibility, intelligence and tactile sense [7-8].

The most important reason to introduce robots in industry workplace is to increase productivity [9], when human are supported by robots, it can increase efficiency of human by improving task performance [10]. “Human-robot collaboration (HRC) is a dream combination of human flexibility and machine efficiency”. The guarantee of human safety plays vital role in the HRC system. There is a vast potential market for HRC workstations in all manufacturing industries whenever this issue have been solved. Many searches have been done to facilitate practical implementation of this topic. Using Virtual simulations of products and production process in manufacturing industry is one of the development solutions in order to increase global competition [11]. By applying virtual simulation it is possible to reduce the product development time, which is vital for the success of a manufacturing company. Simulation and visualization tools can give the possibility to view, design and evaluate the most appropriate production system.

The terms of “cobots” has been presented by Colgate et al. in a seminar paper in 1996 [12], as passive robotic devices that move with human force as their power source. Paper [13] presented “man-robot cooperation” within a single production cell. A vision system ensures the safety of the human while enabling high levels of productivity. Paper [14] developed the term of “man-robot cooperation”. With passing time this research field has grown and developed to become the human-robot collaboration (HRC) expression. Human-robot interaction (HRI) is another related term. Interaction is more general and cover a number of research area such as cognition, linguistics and physiology research combined with engineering, mathematics, and computer science and human factors [15]. HRC is subset of HRI since HRI includes also the cases where robot is acting on somebody else, while talking of collaboration it means that robot is acting with somebody else to accomplish a common objective. The classification of HRI that helps to define the system of human robot variation in a structured way has been proposed by [16]. The arrangement of HRI incorporates robots utilized in healthcare and in open and domestic situations, with human or zoomorphic interfacing with the human and with different sorts of versatility levels.

2.2. Human robot collaboration/interaction

Robotic applications which may react to fluctuations methods in their present industrial environment can improve the productivity of the processes; also in context-aware robotic manipulators (not completely isolated from the rest of production line) the manufacturing process cost can be reduced in terms of space and time (fenceless robotic cells and more subtasks performed simultaneously).

The concern of H-R collaboration/interaction scenarios can be categorized into:

Working areas co-sharing in mutual exclusion: “passive” HRC where Robot runs with full power in absence of men, and use a gradually reduced power in presence of men. The behavior is differentiated a priori according to the working areas and the robot reaches the rest condition when unforeseen presences are detected “close to” the Robot.

Passive robot used as power actuator: the Robot is not “autonomous”: it can’t execute any job and/or run any motion program in automatic state; it is totally subservient to the will of the human operator. Men and Robots, if not executing autonomous task, might be in contact.

Human/robot “active” cooperation; the robot has an active role in the task execution and/or motion program. The Robot is “active” but not “autonomous”: “autonomy” requires “intelligence” and “awareness” of the Robot.

The different forms of Human Robot Collaboration are presented on Figure 2.1.

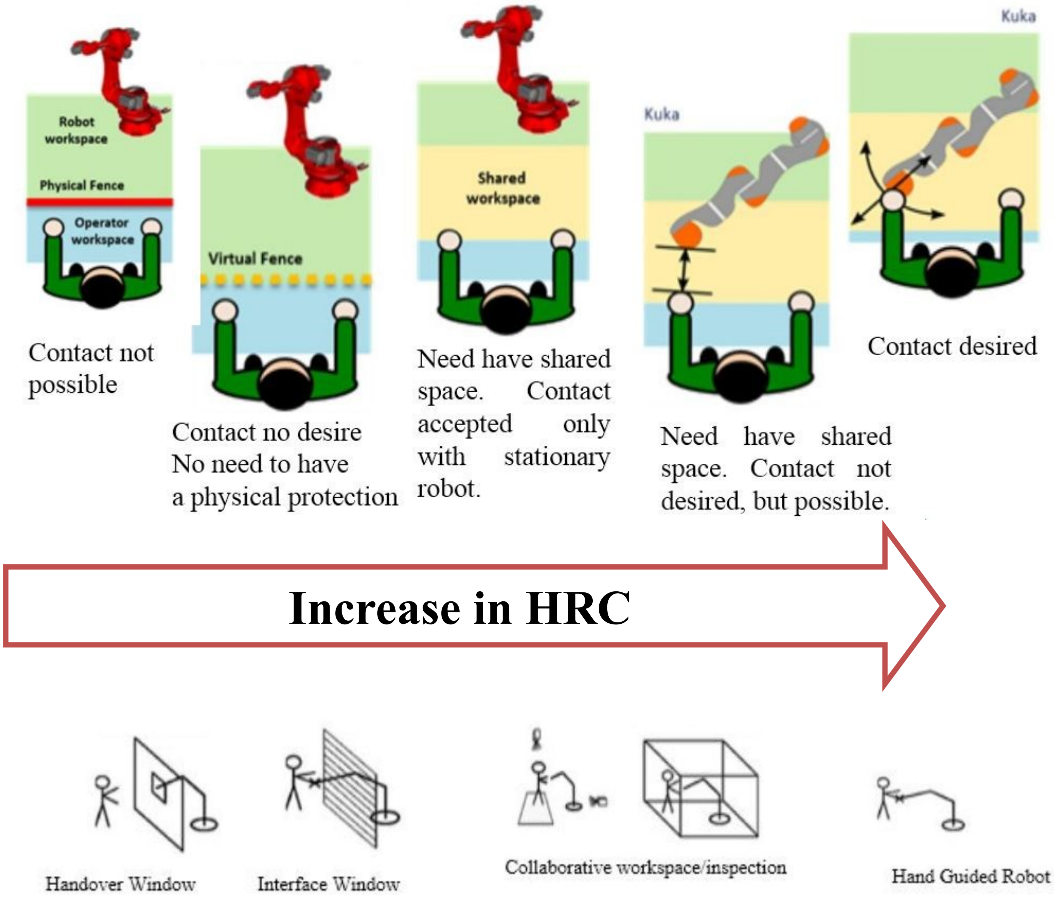

Figure 2.1. Different forms of human robot collaboration

Collaboration modes between human and collaborative industrial robot are presented in the ISO standard ISO 10218 [6] separated into four modes: safety-rated monitored stop, hand guiding, speed and separation monitoring, and control- and force-limiting. These are showed [6, 17-18] in the taking after way "Safety-rated monitored stop" is the least complex of collaboration mode: when a human operator enters the automated work region, the robot stops and when the human clears out the range, the robot framework naturally resumes its activities. "Hand guiding" empowers the human to control the automated end-effector through assigned controls while standing in the mechanical work range and moving the end-effector to an assigned position.

When the human exit the zone, the robot begins its operation from that unused position. "Speed and separation monitoring" empowers the human to be seen in the automated work region while the robot is in operation. The separation between the human and the robot is continually measured and when predefined edges are passed, the robot either moderates down its speed and eventually stops or moves in reverse direction away from the human, all depending on the modified reactions. A "power- and force-limiting" framework incorporates a weak and moderate robot (compared to the standard industry robot) in case of a collision that is designed does not harm human.

Indeed in spite of the fact that the collaborative methods are characterized in the current robotic standard, the conceivable outcomes to construct these Human-Industrial Robot Collaboration (HIRC) frameworks in industry are constrained. Individual safety legislations in industries are administered by the machine mandate [19], which refers to blended measures to meet safety requests. Robots and robot framework safety are regulated by ISO 10218. The requirements of standards typically consist of a few kinds of walls (physical or certified sensors acting as a fence) encompassing a conventional industrialized robot [20]. In HIRC frameworks the robot is still considered unsafe, and the security of the human has to be ensured by frameworks other than walls; awesome inquire about activities are made in this advancement. Current state of the technique presents numerous perceptiveness cameras administering in the HIRC region [21-23], mechanical control frameworks having control of robot positions and developments [22-24], certified sensors helping the depth cameras [23,24] and a organizing unit that is interfacing all these frameworks into the objective of "a safe network of unsafe devices".

2.3. Related robot hazards

When robots have been introduced into industry in the past, the safety of robot did not ask requirements by manufactures and users. With passing time the issue about robot safety received much attention. Robots are not designed for specific task dissimilar to other machines. The central design of robot is motion flexibility which is causes at some extent risk to be injured. Robot can be freely programmed for different velocities and motions on each individual axis, can continuously move in up to n axes, variety range of motion and intersect activity with human and other machines and structures.

During the years while utilizing robot in the production plants, there have been many accidents, including fatal accidents. A Japanese robot survey declared the causes of 18 accidents as following: wrong movement of robot and outer failure equipment during manual tasks (teaching 1, testing 2, repair 3, etc.), operation of tasks, entrance of operator into robot area without authorization and other reasons.

Figure 2.2 illustrate a ratio relation of these factors, where it is seen that accidents occurring. As figure shows during the robots automatic mode of operation the value of accidents do not overcome the value of 5,6% whereas for manual mode this value grasps 16,6%. This means that most probably chances of robot accidents happen during repairing, teaching or when human operate task in close vicinity to the robot.

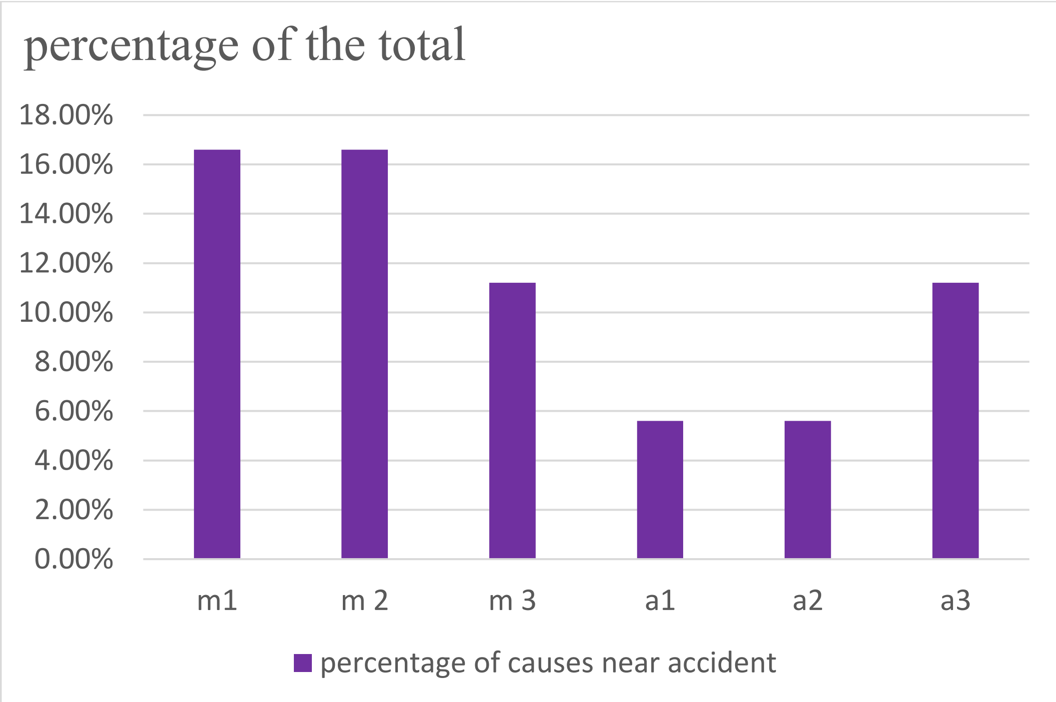

Figure 2.2. The ratios of failure causes near accidents [26]

The type of accidents might vary from no injury to fatality. The accident results can be divided into two categories: pinch-point (a human part of the body clamped between robot parts or between the robot itself and some external item) and impact. [27] The raw date on several injuries connected to robot operations was cited in the report published by the United Auto Workers (UAW) union. [28]. The injury sorts are contained within cuts or abrasions, resulted from contact with a sharp or abrasive surface, as well as more serious injuries including bone fracture resulted from manipulator pinch points or direct crush loads.

At the time operator is near robot to do tasks and robot works with large load if the most potential impact and injury happens very likely leads to fatality. The finger, hands, head and chest are utmost common body parts involved into potential accidents. (See Figure.2.3).

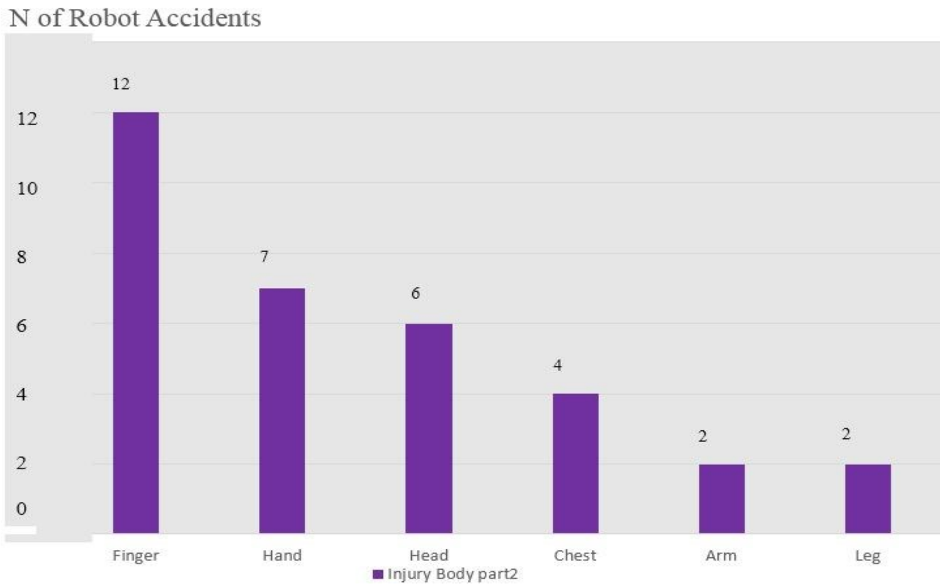

Figure 2.3. The 36 robotic accidents failure by types of injury [28]

Robot accident origins can be categorized into three main classes: engineering, human behavior and environmental conditions. The first category is engineering which is contains the failure of robot mechanism (electrical, mechanical), sensors, robot controller and associated equipment (electrical, mechanical, software). The significance if these failures are abrupt motions, runaways, arm high uncontrolled speed, acceleration, force, energy ejections, etc.

The second category is behavioral class which contains human error factors which may originate from inadequate safety training, incorrect ergonomic workplace or equipment design, high task cognitive load, inadequate task distribution, etc. The consequences can be: loss in situational awareness, attention and hazard perception, unauthorized entry into dangerous work space, erroneous robot operation and task performance, etc.

The third category is environment class which is related to the conditions required for a normal robot and convenient human operations. This implies ambient temperature, humidity, lighting, noise and vibration levels, as well as ergonomic factors consideration in equipment and workstation design.

Industrial users of robots and manufactures have improved the robot safeguarding methods, such as: features of robot safety with different design, perimeter safeguarding, intelligent controls, personnel perception enhancement and protection, work cell, etc. Although this research field still needs more attention toward systemization and standardization of the elements.

2.4. Safety standards for robots

ISO 12100:2010 specifies basic terminology, principles and a methodology for improving safety in the design of machinery. It specifies principles of risk assessment and risk reduction to help designers in achieving this objective. These principles are based on knowledge and experience of the design, use, incidents, accidents and risks associated with machinery [29]. The American National Standard for Industrial Robots and Robot systems addressed the safety requirements for personal interacted by robotic manipulators that are utilized in the work environment. Factories and industrial plants frequently used this standard for robot operational safety [30].

According to this standard for safety of operator, the robot arm reachable region is defined and should be separated from the space used by the workers during operation, this region should include any tools loaded by the robot. One option for applying this standard is to implement safeguarding in order to prevent hazard, or to remove the causes of hazard without needing any specific action by operator(s). The recommended action to be taken by the robot control system upon identifying an intrusion into the defended space is an emergency stop actuation that eliminates all drive controls and all other vitality sources. Also according to ANSI/RIA 15.6, European standard EN-775 [31] requires operator’s nonattendance inside the safeguarded space amid programmed robot operation.

This means that the robot should be bordered by safeguarding space and it must be working in a defined space with number of tasks to be performed with operator standing outside of safeguarding zone. Other safety guidelines were developed by the Occupational Safety and Health Administration (OSHA) [32], where industrial robots and robot safety systems are considered with a stress on independence of robot. IEC 1508 [33] has implemented a significant hazards list: standardization, where the main objective was to provide a basis for safely automating process plant, machinery, medical devices and other industrial equipment.

This standard contains safety management, risk assessment methodology, requirements for software and programmable electronic system architectures. ISO 13849-1:2006 [34] is dedicated to the performance level of design requirements of performance level “d” with structure category 3 for safety-related parts of control systems as demonstrated in Figure 2.4. This is the starting point for the evaluation of safety function contribution to risk reduction.

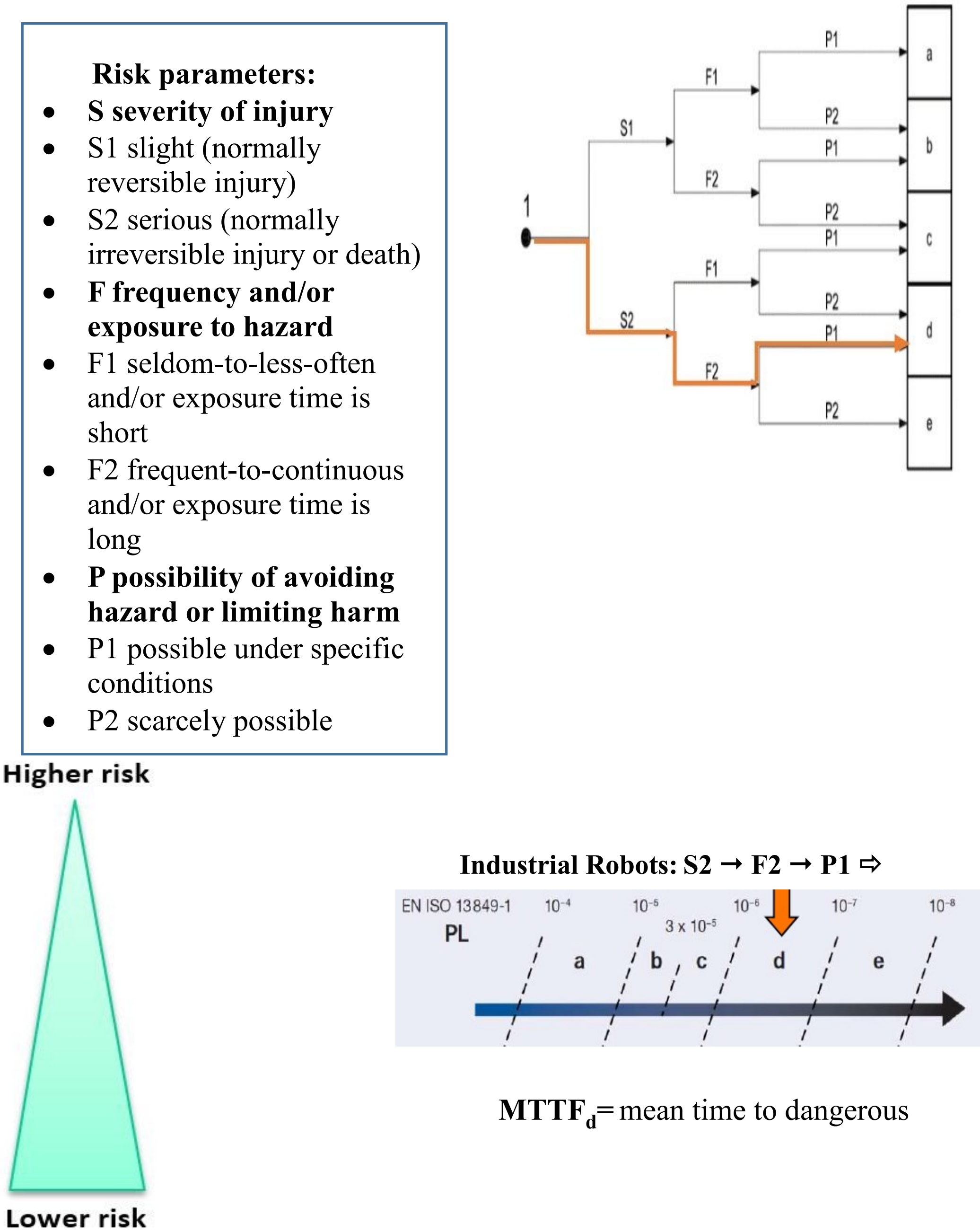

Figure 2.4. ISO 13849-1: Performance Level

2.5. Category of ISO 13849-1:

Performance requirements are presented in Figure 2.5.

• "Safety-related parts of control systems must be designed to meet the requirements of PL "d" with structure category 3 as described in ISO 13849-1:2006"

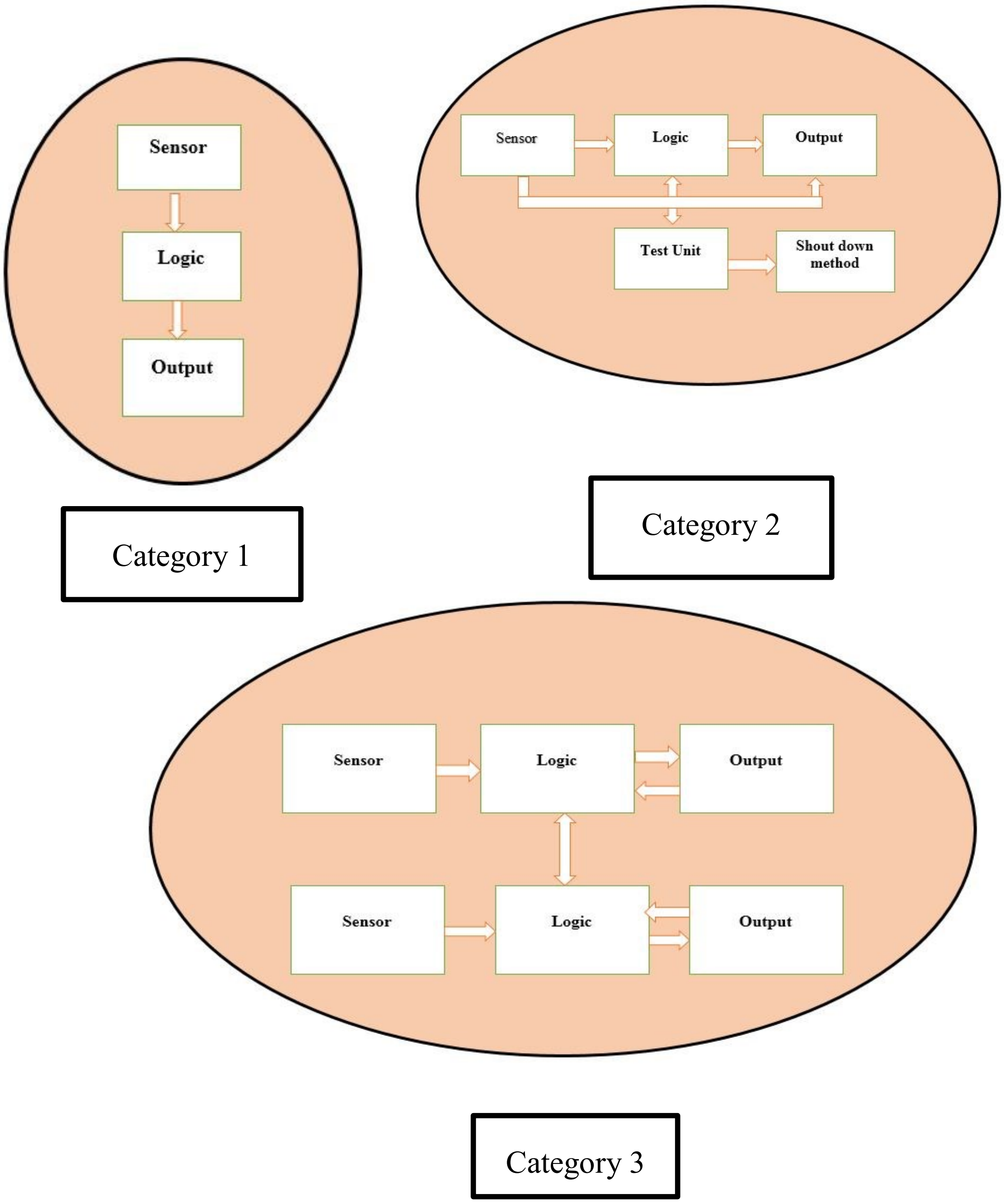

Figure 2.5. Categories of performance requirements according to ISO13849-1.

The International Organization for Standardization (ISO) developed the ISO 10218 [35] standard (the international equivalent of R15.06) the new concepts of industrial robot safety were presented. It is divided in two categories: guide lines for the assurance of safety in design and construction of the robot and for the safeguarding of personnel during robot integration, installation, functional testing, programming, operation, maintenance and repair. Part II has been recently modified and it allows operator to cooperate due to presented limits for speed, power and additional safeguard installation, although the operational space is not complete and obviously discussed. In the following further details will be given about standards and technical specifications, also in Figure 2.6 the schematic of standard requirements in manufacturing systems are presented.

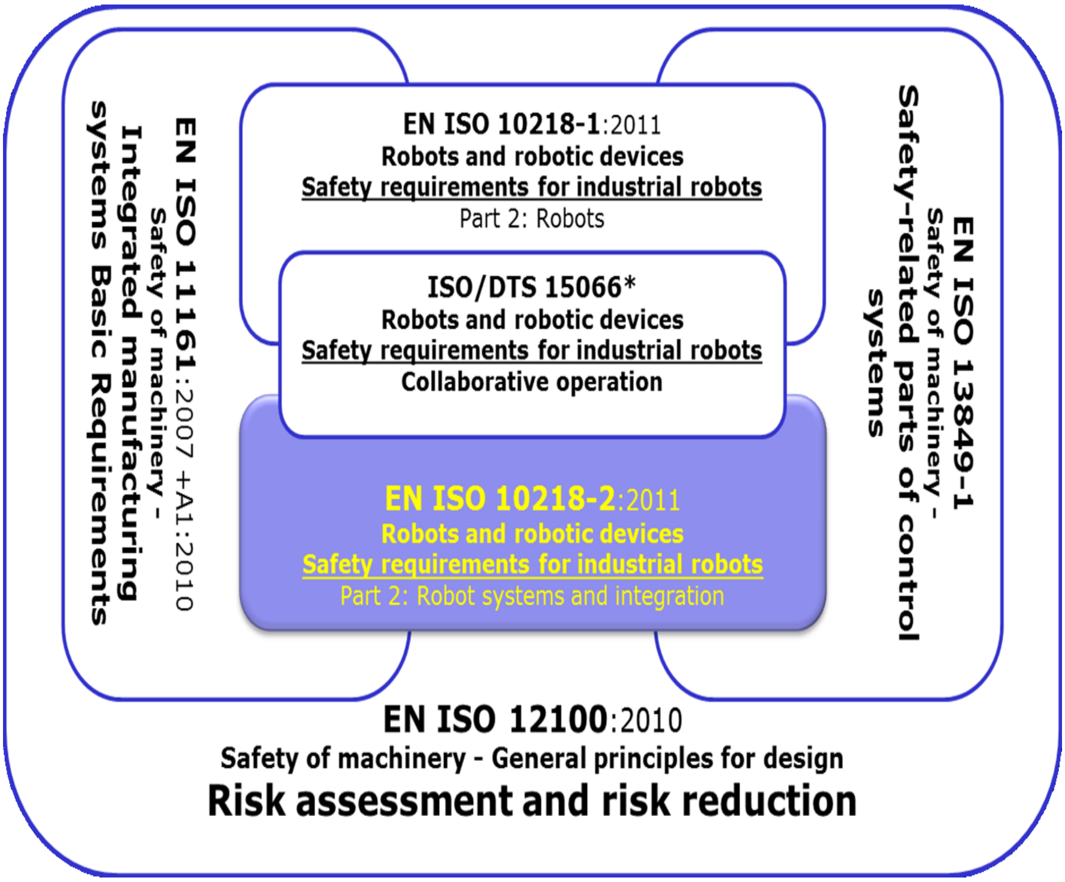

Figure 2.6. The schematic of standards requirements in manufacturing systems

2.6. Quote from ISO 10218-1 & 2:2011

ISO 10218-1:2011 (Part 1: for the robot) [6, 18]

5.10 Requirements for collaborative operation

5.10.5 Power and force limiting by design or control

The function for power or force limitation of the robot must meet the requirements of 5.4. If a limit value is exceeded, a safety stop must be triggered.

5.4 Safety-related performance of the control system (hardware/software)

5.4.2 Performance requirements

Safety-related parts of control systems must be designed to meet the requirements of PL “d” with structure category 3 as described in ISO 13849-1:2006 [34], or to conform to SIL 2 with a hardware fault tolerance of 1 with a Proof-Test interval of no less than 20 years (see IEC 62061:2005).

This means in particular:

a) A single fault in any of these parts does not lead to the loss of the safety function;

b) Whenever reasonably practicable, the single fault shall be detected at or before the next demand upon the safety function;

c) When the single fault occurs, the safety function is always performed and a safe state shall be maintained until the detected fault is corrected; and

d) All reasonably foreseeable faults shall be detected.

The requirements a) to d) are considered to be equivalent to structure category 3 as described in ISO 13849-1:2006.

ISO 10218-2:2011 (Part 2: integration of Robot System)

5.11 Collaborative robot operation

5.11.1 General description of purpose

Collaboration is a special kind of operation between a person and a robot sharing a common workspace. It is only:

– used for predetermined tasks;

– Possible when all required protective measures are active; and for robots with features specifically designed for collaborative operation complying with ISO 10218-1.

5.11.5 Operation in the collaboration space

5.11.5.5 Power and force limiting by design or control

In robot systems designed to control hazards by means of energy or force limitation, robots that conform to ISO 10218-1 must be used. The parameters for power, force and ergonomics must be defined in the risk assessment.

ISO 10218 only describes the requirements in very general terms, whereas IS0/TS 15066 [36] provides more guidance. In essence, ISO/TS 15066 is designed to build on and supplement the limited requirements laid out in existing standards. Note that ISO/TS 15066 is not a standard, it's a technical specification.

2.7. ISO/TS 15066 (ISO TC 184/SC 2)

Defines occupational safety requirements for collaborative industrial robots and their work environment.

Supplements and specifies the requirements for collaborative industrial robot operation of ISO 10218-1 and ISO 10218-2.

- Details hand guiding management and relative requirements.
- Gives quantitative limits for distances, force, pressure, speed, geometrical characteristics of the tools…
- Details requirements in collaborative robot operation for:
    - ✓ the end-effector (shape, behaviour)
    - ✓ the tooling's and other equipment necessary for performance of the work tasks
    - ✓ safety-rated monitored stop
    - ✓ speed and separation monitoring
    - ✓ power and force limiting
- Gives Medical/biomechanical and ergonomic requirements
- Gives methodologies for test procedures to validate that acceptable force and pressure limits are not exceeded.

2.8. Key points of standards

EN ISO 10218-2:2011: Collaboration is only:

- used for predetermined tasks;
- possible when all required protective measures are active;
- Possible for robots with features specifically designed for collaborative operation complying with ISO 10218-1.

- In robot systems designed to control hazards by means of energy or force limitation, robots that conform to ISO 10218-1 must be used. The parameters for power, force and ergonomics must be defined in the risk assessment.
- EN ISO 10218-1:2011:
- The robot is only one component in a robot system and as such is not sufficient for safe collaborative operation.
- Application involving collaborative operation must be investigated and defined in the risk assessment.
- ISO/TS 15066 - recommendation (technical specification)
- Supplements and specifies the requirements for collaborative industrial robot operation of ISO 10218-1 and ISO 10218-2.
- Under no circumstances a risk for injuries with higher severity than category 1 of the Abbreviated Injury Scale (AIS) and more severe than with the codifications for surface injuries of the ICD-10- 2006 can be tolerated;
- Taking into account the intended use, the injury risk for the sense organs (eyes, ears, nose and mouth) shall be lowered sufficiently through personal protective equipment (e.g. goggles);

2.9. Details of ISO 15066

2.9.1. Collaborative robot technical specification ISO/TS 15066

ISO/TS 15066 related to Robots and robotic devices – Collaborative robots
– Develops on collaborative guidance in ISO10218-1 and ISO 10218-2: 2011
• ANSI/ RIA R15.06:2012 is ISO 10218-1 & -2.
• The next modification of ISO 10218-1 and -2 (ANSI/RIA R15.06) will be continued of TS 15066 researches and achievements.

2.9.2. ISO & R15.06 “Words”

Shall: Normative or mandatory necessity
Should: Recommendation or good exercise
May: Permissive or allowed
Can: Possible or capable – statement of fact
Notes are informative: make available information or explain concepts.
If you see a “shall,” “should” or “may” in a note –it is an error.

ANNEXES can be NORMATIVE or INFORMATIVE
All annexes can contain shalls/ shoulds/ mays and cans. If you CHOOSE to use an informative annex, you use all of it as written (no “cherry picking”)

2.9.3. Terminology

Robot– Robot arm & robot control (end-effector or part is not included)
Robot System– Robot, end-effector and work piece

Maximum space
–Space within which a robot system CAN move

Constrained space
–Portion of the maximum space limited by restrictive devices that establish limits which will not be exceeded Operating space
–Portion of the restricted space that is actually used while performing all motions commanded by the task program Safeguarded space
– Space defined by the perimeter safeguarding Operator(s)
– All personnel, not simply production operators.
Includes maintenance, troubleshooting, setup, cleaning, production...

2.10. Spaces from R15.06 and ISO 10218

The performance requirement of thsi ISO is as following:

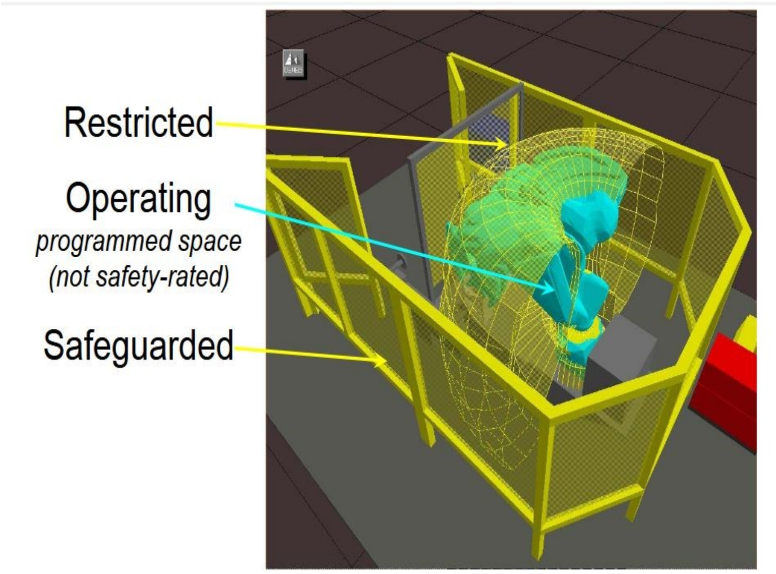

Figure 2.7. Performance requirements ISO13849-1

2.11. What is a collaborative workspace?

•According to TS 15066, 3.3

Improved from what is in R15.06 and ISO 10218

–Whenever human and robot system (including the work space) in operation space can complete duties or tasks simultaneously during production operation it can be define as collaborative workspace as presented in Figure 2.8.

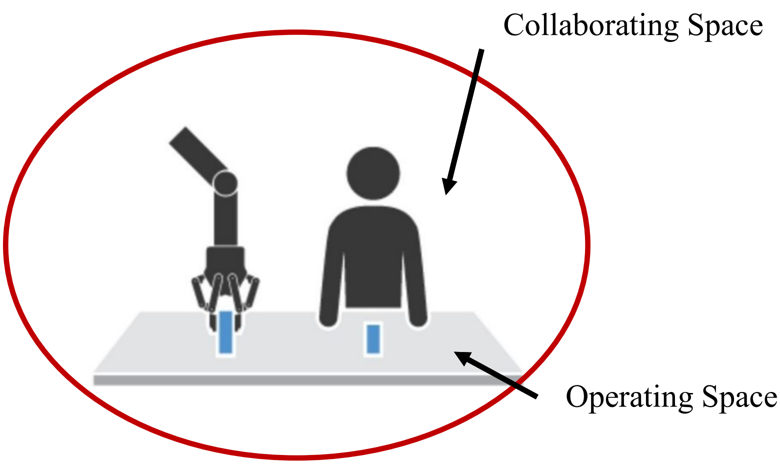

Figure 2.8. Collaboration workspace

2.12. Definition of collaborative operation

It will be defined by:
–The TASK: which is performed by robot SYSTEM is doing
–The SPACE: which location the task is being performed

2.13. Collaborative risk assessment

Risk assessment characteristics of collaboration will be defined by:
• Same process/methodology as "standard" (non-collaborative) application
• Plus need to assess added conditions (TS, 4.2)

- Intended and reasonably foreseeable contact(s) between portions of the robot system and an operator (human)
- Contact type to be determined (transient or quasi-static) for each body part(s) affected
- Frequency and duration of contact

In table 2.1 differences between traditional and collaborative robot application in layouts are presented.

Table 2.1. Different concept between traditional and collaborative of robot application

Traditional Applications	**Collaborative Applications**
Inherently safe design measures	
Process design, Limiting access, layout	Process modifications, reduced energy, compliant(soft) materials
Safeguards and SRP/CS	

Fixed & interlocked guards **Sensitive protective equipment** **Hard axis limits or Safety-rated soft axis and space limits** **Safety functions for protective devices and reducing risks**	Safety-rated speed, positions Safety-rated soft axis and space limits Safety-rated torque sensing(impact) More....
Information for Use	
SAME or SIMILAR	

2.14. Types of collaborative operation

Collaborative operations are divided into the following categories:

- Safety-rated monitored stop
- Hand-guiding operation
- Speed & separation monitoring
- Power & force limiting

2.15. Safety -rated monitored stop

Under specific conditions the operator can have direct interaction with robot system:

• Before operator enters into robot space the Safety-rated stop state happens
• Drive power remains on
• After operator leaves collaborative area the Robot motion will be resumed without additional action
• If stop condition is disrupted, protective stop should be issued.

2.15.1. Applications of Safety-Rated Monitored Stop

Applications of Safety-Rated Monitored Stop are as following:

• Loading or unloading of parts by end effector
• Examinations of work in process
• When in collaborative workspace moves only robot or operator
• combined by other collaborative technique

2.16. Robot system requirement

The figure 2.9 shows the requirements of safety-rated monitored stop in collaborative workspace.

Robot <system> motion or stop function		Operator’s proximity to collaborative workspace	
		Outside	Inside
Robot’s <system> proximity to collaborative workspace	Outside	Continue	Continue
	Inside and moving	Continue	Protective stop
	Inside, at Safety-Rated Monitored Stop	Continue	Continue

Figure 2.9. Requirements of safety-rated monitored stop method

2.17. Hand-Guiding

automatic, not teaching

Operator to transmit motion commands applies a hand-operated device as presented in Figure 2.10

–Drive power remains on

• Hand-operated device (includes an enabling device) grasped by operator, motion/ operation are activating

• Until operator completely leaves the collaborative are the robot cannot resume motion.

2.17.1. Applications of hand guiding method.

Robotic lift assist

•Highly variable applications (acts like a manually "tool")

•Limited or small-batch production

Figure 2.10. Hand Guiding Method

2.18. Speed & separation monitoring

Figure 2.11 shows the schematic of Speed and Separation Monitoring method and Figure 2.12 presents the side and top views of human and robot positions during collaboration. The speed and separation monitoring method is described with specific details as following:

- In collaborative zone robot system and operator can move simultaneously
- At all times the minimum protective separation distance remains between the operator & robot system
- Protective facilities are required to determine the approach (reducing protective separation distance)
- To remain the minimum protective separation distance, it is needed to decrease the speed of robot (safety-rated)
- Protective stop command is obligated to robot whenever the protective separation distance is disturbed.

2.18.1. Applications of speed and separation method

The third collaborative method: "speed and separation monitoring" presented in Equation(1)during Simultaneous tasks and direct operator interface.

$$S_p\left(t_0\right) = S_h + S_r + S_s + C + Z_d + Z_r \qquad \text{Eq(1)}$$

where

$S_p(t_0)$ = Protective separation distance

S_h = The operator's change in location

S_r = The robot's change in location

S_s = the robot's stopping distance

C = the intrusion distance that a part of the body can move toward the hazard zone prior to actuation of the safeguard

$Z_d + Z_r$ = Position uncertainty for both the robot and operator

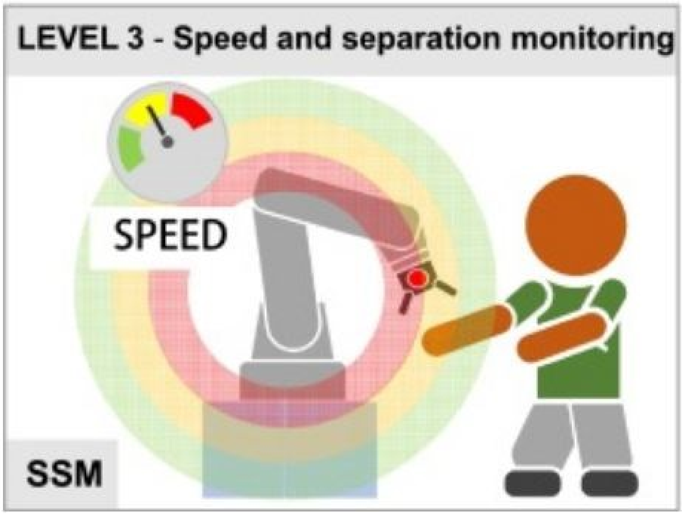

Figure 2.11. Safety-Rated Monitored Stop

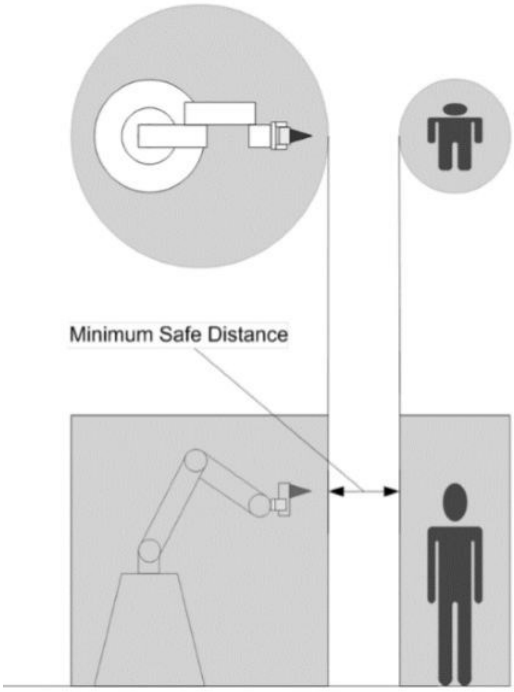

Figure 2.12. Top view of speed and separation method

2.19. Power and force limiting

Physical contact between the robot system (including the work piece) and an operator can occur either intentionally or unintentionally as illustrated in Figure 2.13.

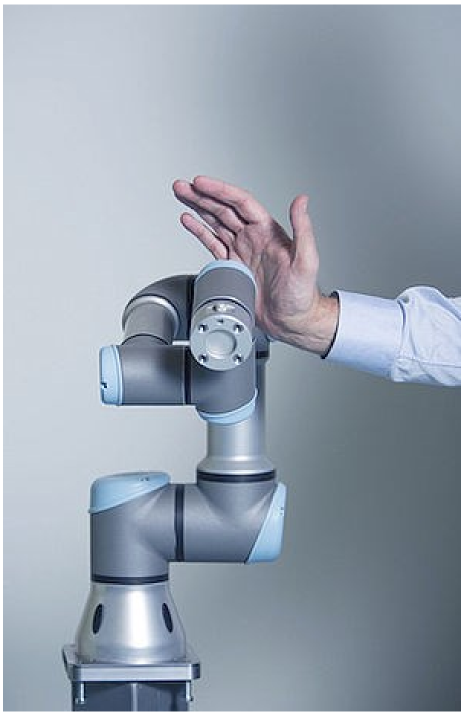

Figure 2.13. Power and force limiting

It is important to mention that:

- Applying power and force limiting is required that the robot system should be specifically designed.
- Forces that can be applied are obligatory to be limited to robot, end-effector, work piece.
- When contact occurs the robot system should react.
- Quasi-static (pressure) or transient (dynamic) are the kind of contact.

Applications of power and force limiting method are:
• Small or highly variable applications
• Conditions requiring frequent operator presence

2.19.1. Power and force limiting conditions

As presented in Figure 2.14 and 2.15, conditions for risk reduction of potential contact in power and force limiting method, where there will be no harm to the operator are as following:

- Identify conditions for such contact to occur
- Evaluate risk potential for such contacts
- Design robot system & collaborative workspace so contact is infrequent and avoidable
- Consider operator body regions as shows in Figure 2.16 and Table 2.2, origin of contact event, probability or frequency, type (quasi-static or transient), forces, speeds.
- Contact to head, throat & neck to be prevented

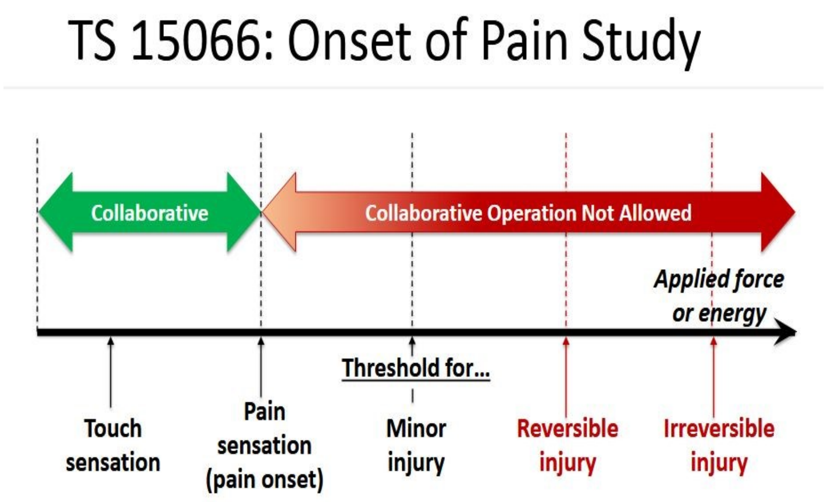

Figure 2.14. Onset of pain and injury study

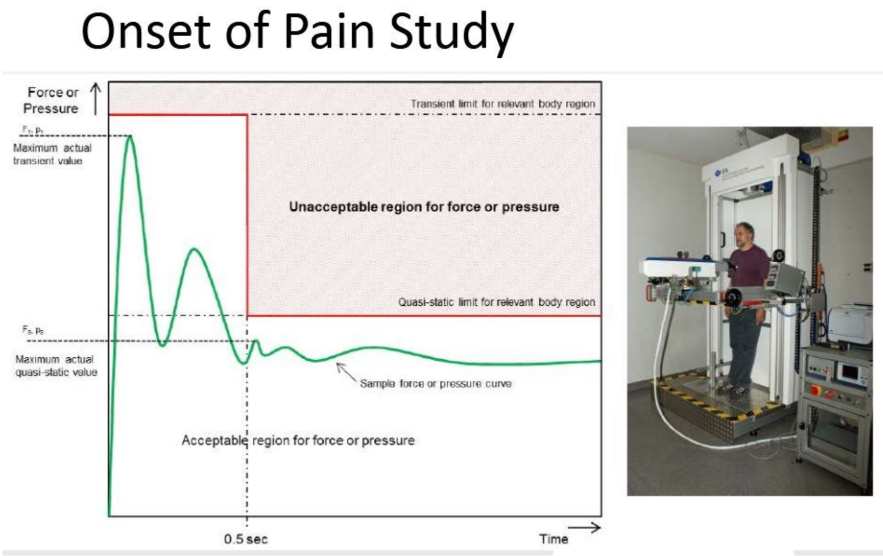

Figure 2.15. Onset of pain study

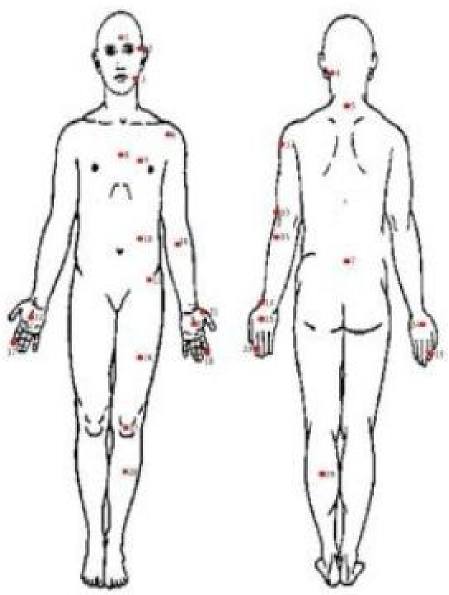

Figure 2.16. Onset of pain study on body region

Table 2.2. Body region

Body Region		Specific Body Area
Skull and Forehead	**1**	Middle of Forehead
	2	Temple
Face	**3**	Masticatory muscle
Neck	4 to 5	Multiple
Back & Shoulder	6 to 7	Multiple
Chest	8 to 9	Multiple
Abdomen	10	Abdominal muscle
Pelvis	11	Pelvic bone
Upper arms & Elbow joints	12 to 16	Multiple
Hand and Fingers	14 and 15	Multiple
Thighs & Knees	26 to 27	Multiple
Lower Legs	28 to 29	Multiple

2.20. Risk assessment

The human safety can be mostly improved by requirements for training programs and for personnel safeguards in teach-mode operation, but in any case interaction is not allowed during the robot autonomous operation. However, due to a new tendency in robotic applications with transition from isolated, structured, industrial environments to interactive, unstructured, human accessed workspaces, the above mentioned approach is no more covering possible situations and so is no longer applicable. Despite of these safety standards and their guidelines, there are still a number of serious accident occurrences related to the robots. This means that every time during HRC safety aspects should be considered and carefully checked.

2.21. Related techniques for hazard assessment

- Hazard assessment related to robot implementation is helpful to detect potential weaknesses in design through systematic documented considerations on the following categories [37]:

1. All possible ways in which robot can fail.
2. Causes for each mode of failure.

3. Effects of each failure mode on robot system reliability.
4. Probability of occurrence of each failure mode.

Many analytical methods have been proposed to understand how accidents occur by failures and errors, also to reduce the probability of their happening [38].

1. Preliminary Hazard Analysis (PHA) is the operative foundation systems for hazard analysis. It should start with the collection of necessary raw data related with the design, production, and hazard characteristic of the system. The main four classification are: hazards, causes, main effects, and prevention controls. The hazard properties and corrective/preventive measures are uncertainty indicators of possible hazards and their potential solutions.

2. Failure Mode, Effects and Criticality Analysis. FMECA investigates the elements of the system and all of the failure possibilities that can happen during various real operative situations. In this analysis, each task and function of components should be determined. Afterwards, the reasons for error and failure of components are recognized, the consequents effects are listed and the event probability estimated, also on the basis of historical data. This type of analysis indicates elements of a system that have consequently potential hazards, the failure modes can be listed from the highest probability of occurrence to the lower. Finally the modifications needed to improve the robot design and obtain a better performance are identified.

3. Hazard and Operability Study (HAZOP) is one the most systemic forms of hazard analysis. In the first step the system and all of its subsystems from which data will be needed are defined. Then it determines potential interactive and complicate hazards in the system, analyzes and examines the data to put in evidence potentially hazardous areas.

4. Fault Tree Analysis (FTA) is one the most influential tools for logical analysis of system hazards. FTA uses logical links to illustrate quantitatively (and qualitatively) the functional relationships between the different components of a complex system. Then it is possible to evaluate probability of failures of the system staring from the base elements and climbing up along the tree. This procedure finally describes the possible hazards that may happen as failure of the relationships between the components of system. FTA employs a pyramid-style tree examination to begin from one top event i.e. the main undesired failure (e.g., accident or injury) down to the beginning causes of the hazard as illustrated in Figure 2.17. [39] FTA exchanges information with FMEA and takes into account the combinations of occasions driving to risks (recognized amid the risk and hazard assessment).

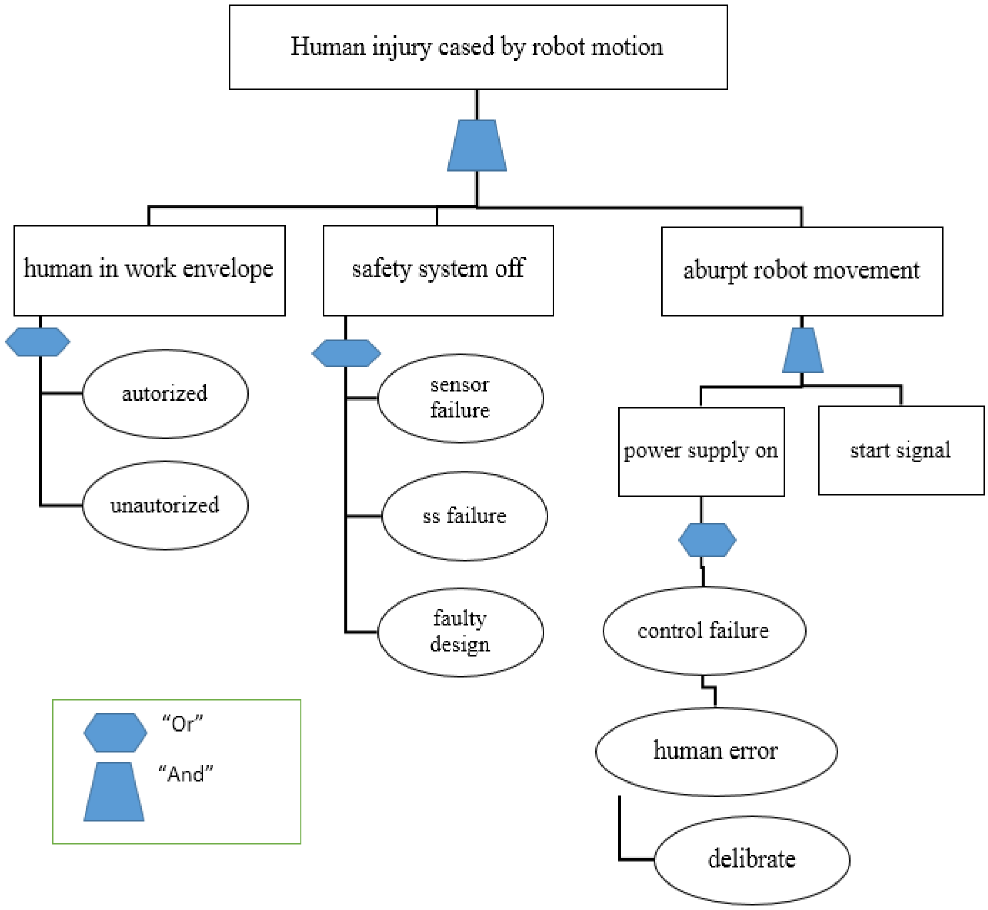

Figure 2.17. An example of the FTA method is presented for the event "unexpected robot motion".

This method has top-down approach to analysis of failure. It starts with an unwanted event called a top event, and then asks for the identification of how this top event can be influenced by individual or combined lower level failures or events (e.g. human action, safety system and robot states). For the particular application of the FTA analysis, the top event is a hazard in a safety that must have been foreseen and thus identified by the previous techniques. FTA analysis can be quantitative or qualitative, but in most cases it is not easy to develop the quantitative analysis because all of the failure possibilities should be assessed (and measured with a probability) then the occurrences of the top-event can be calculated as result the qualitative analysis is done.

First, the failure interactions can be demonstrate in a tree, and second, protection mechanisms can be integrated with events (including human errors).

The goal of the qualitative analysis is to investigate the minimal cut *sets* (relationship between the top event and the primary events) which denote the primary events that will cause the top event. Almost all the possible danger in human robot collaboration environment are the result of unsafe conditions and unsafe action.

FTA and FMECA between other analyzed techniques represent more secure methods for robot safety analysis in HRC domain.

2.22. Standardized risk assessment and reduction approaches

The aim of risk assessment is to collect and produce information about the machine hazards to design and update the specification safety design. The required information for machinery risk assessment is to identify the planned and unplanned use of the machine also, its functions and structures (see Fig.2.18). [40] Risk assessment method is much used and discussed in some safety standard of robot. In risk assessment techniques contain several steps which are determined by the category of risk and the reduction methods.

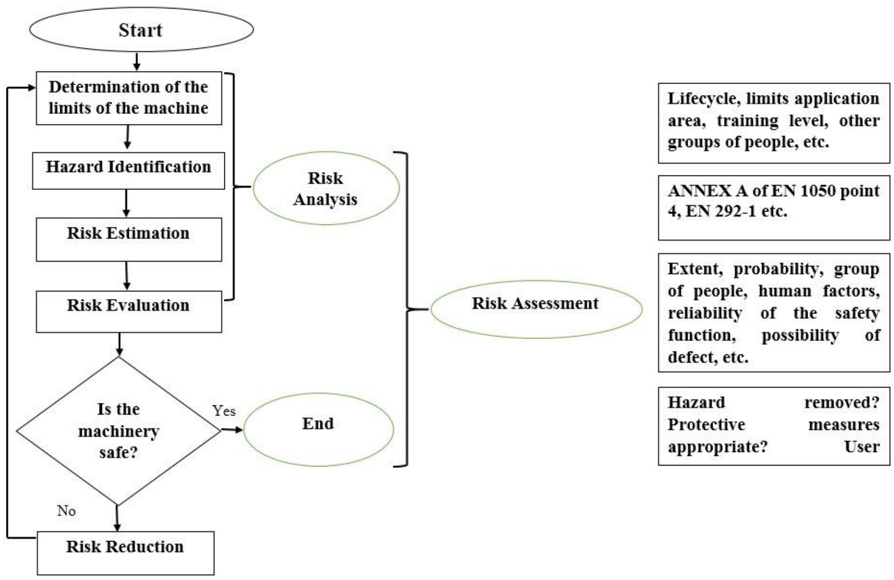

Figure 2.18. Risk Assessment Algorithm according to the Machinery Standard [40]

For instance, in the Robot Safety Standard ANSI/RIA R15.06 [30] these steps are:

1. To determine the robot application field, to identify all limitations linked with the intended use (layout, time, dynamical, kinematical, mechanical constrains, software needs, etc.).
2. To identify hazards for each robot task analyzing methods of operation, ways of interaction with human workers and the mechanisms failure probability rate estimations.
3. To evaluate risk category for each hazard in terms of probability, likelihood and severity of the occurrence of an injury or damage. This step involves the development of a risk assessment matrix with the three primary categories: severity of harm (S1, S2), frequency of exposure (E1, E2) and likelihood of the hazard avoidance (A1, A2).
4. To determine whether the estimated risk is tolerable or not.
5. To reduce the risk, if it is not acceptable, by means of the corresponding safeguarding systems installation or standard procedures application.

A standard approach in a risk reduction (see Fig. 2.19) requires to apply all necessary measures in a hierarchical order, where the primary step should be always the hazards elimination by the work cell redesign, while the next steps should involve the incorporation of safeguarding technologies, training, warning procedures, and personnel safety equipment definition.

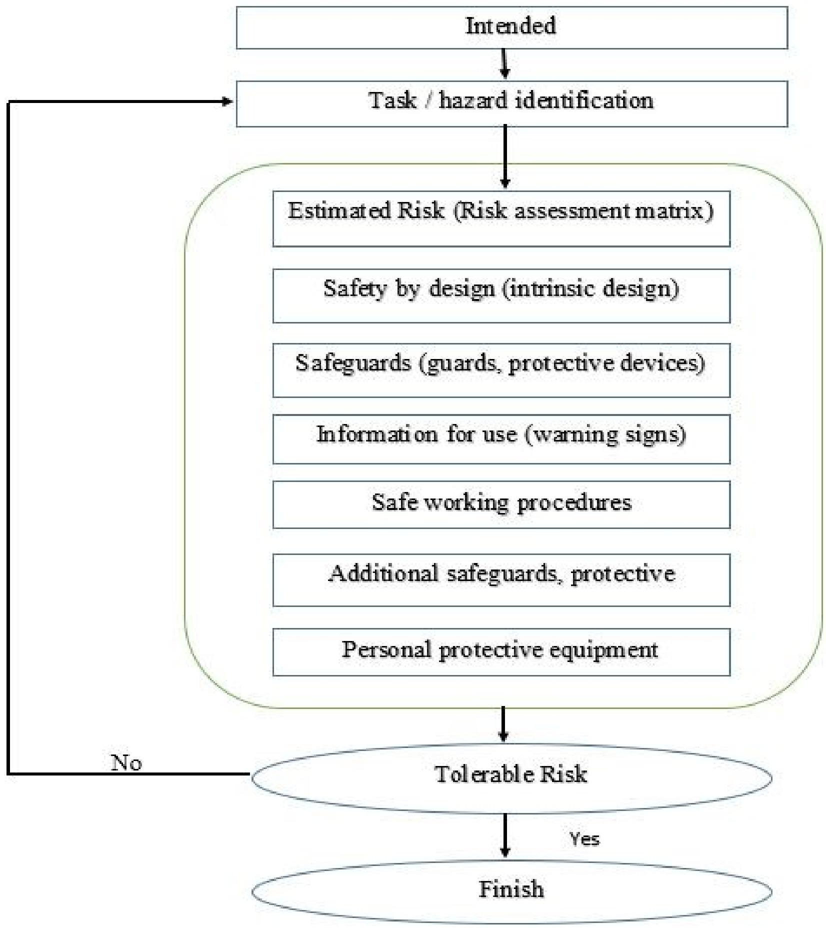

Figure 2.19. Generalized risk reduction algorithm stated in the robot safety standard [30]

According to ANSI/RIA, standard suggests a strategy to reduce the risk, this can be approximately categorized into three classifications:

1. Fault avoidance (preventing or reducing the occurrence of faults by selecting highly reliable components); robot system fault tolerance enhancement (in case of failure of components system lose their functionality gradually, not catastrophically by including system redundancy, error correction and recovery) and fault immediate, reliable detection;
2. Select and locate proper safeguarding
3. Implement and determine risk category for safety circuit requirements.

To collect manually all these categories can be issue, especially for multitask applications which contain a number of factors that may affect the final risk category. Furthermore, these methods are oriented to machinery, where the influence of human factors is not very relevant.

2.23. Identification of safeguarding and protective zones

To better distinguish hazard, in general, the robotized workstation is divided into two volumes: the robot movement zone (region around the end effector) and approach zone. More detailed differentiation was provided by the analysis developed at the US National Institute for Standard and Technology (NIST) [41], where three safety regions were identified:

Zone 1- A safety region outside the reachable work area of the robot, where safety is achieved in an industrial setting by use of a physical barriers and perimeter sensing devices;

Zone 2- A safety region within the reachable workspace volume of the robot, where an intruder is within reach of the robot, but not in imminent danger of being struck.

Zone 3- A safety region is defined to be the volume immediately around the robot.

Hazard discriminate for robotized workstation are categorized into two sections: the Robot movement area (space around the end effector) and the approach zone. More details can be found in NIST published results [41].

Human Centered Design (HCD) where the human has vital role in the system and development and the whole of tasks and duties in each interaction levels are defined during collaboration with robots. [42] [43]. The areas were classified in to: peer to peer, supervisory, mechanic or maintenance and observation zones. Therefore, in each zone the methodology involves and defines the role of personnel with robotics system during collaboration.

For example, the peer to peer role means the human presence as assistance of robot according to task performance for each personnel ability and skill will be change their contributions. The supervisor role can be considered as controlling and monitoring of the overall situation. This means that the supervisor would evaluate the given situation and monitor the situation with respect to the predetermined goal. In the mechanic role should be focusing on characteristics of robot, electrical and mechanical parts.

The interaction is very limited and, perhaps, it's the most isolated in the role of *bystander*. These two methods can be combined to give with an unused concept in interaction levels dissemination where robot related zones can be connected with a human parts inside the co-operative assignment execution. From the security point of view each level of interaction suggests its claim set of safeguarding implies. For occurrence, the third level is exceptionally well explored and expounded in robotic standardization since there is an apparent association with a tactic device security.

A reasonable set of safeguarding means at two last levels requires more sophisticated protective means and policy since the risk for personnel of being injured by the robot is very high.

2.24. Preventive solutions for the interaction level 3

Safeguarding systems as most efficient standardized level are categorized into 5 classes:

1. Present sensing devices. Laser scanner, light curtains and pressure sensitive mats are used frequently for safety of robotics (see Figure.2.20 a, b), during to interaction between robot and operator with the safety and robot controllers this devices used to detect person moving to robot zone and entering into hazardous area to stop of robot motion. In order to non-contact monitoring of a freely programmable area the laser scanners can be used. Human detection typically applied these sensor classes: Ultrasound detectors, passive and active infrared sensors, capacitive and pressure sensing units, etc. Robot grippers can be also equipped with photo-electric transducers, cameras, force, capacitive, radar, range finder and other sensors to control their own operation conditions and to enhance "awareness" about the ambient environment.

2. Fix perimeter guards. Containing the non-sensor safety devices which are usually installed around a robot work to cover the safety system gates, such as: fixed barriers (fences) and interlocked barrier guards, (see Fig.2.20 c).

3. Awareness system containing of the audio, video alarms (flashing, muting lamps), warnings and awareness barriers.

4. Personnel protection indicates hand, foot switches, teach pendant equipped with enabling switches and emergency stop. Also other task required special protective clothes or some wearable equipment's protective.

5. The safety circuit depending all of safety system levels connected all safety devices to the safety and robot controller. The control system can be provided by programmable safety controller (PLS) or modulator with direct or remote monitoring of integrated safety systems or Safety Relays (see Fig. 2.19 d). Robot control is usually limited to a standard joint boundaries control devices (mechanical switches or software based), excessive load, motor temperature, joints velocity and acceleration monitoring means.

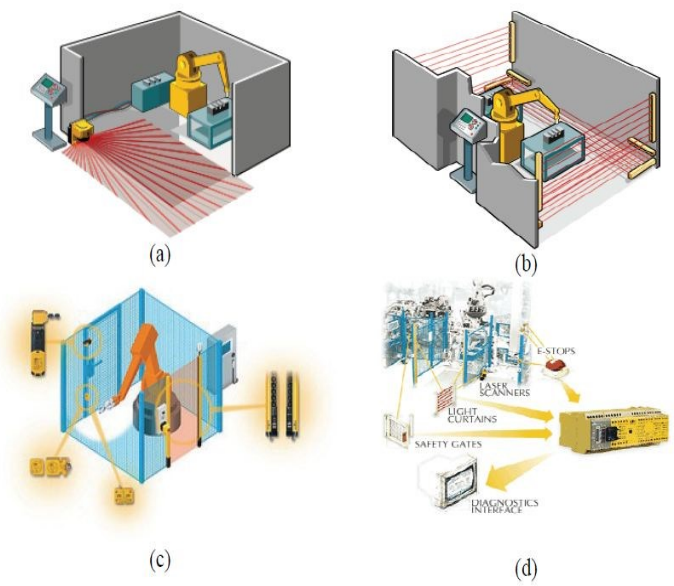

Figure 2.20. Safeguarding Solutions for the Robotic Systems: a) scanning system, b) light curtains, c) guard fence with safety switches integrated into the gates, d) safety controller.

Among the recent solutions for safety in industry results of the KUKA Roboter GmbH can be highlighted. [44], [45] they have developed a safety system for industrial robots incorporating the safety-related fieldbus (SafetyBUS p) in cooperation with Pilz GmbH. The Electronic Safety Circuit (ESC) coupled with SafetyBUS p and Pilz Programmable Safety System (PSS) safety controllers. Fieldbus networks are now widely used for transmitting control data, but not safety-related data. Conventional fieldbus technology is generally prohibited for safety-related use, unless the bus system is designed to meet the requirements of a safety system.

“KUKA Safe Robot” is a technology developed by same group. This robot is more intelligent and sensitive to allow the worker to enter the robot area and interact and guide the robot manually. The “Safe Operation” and “Safe Handling” are most important functions, which monitor the velocity and acceleration of the robot axes, enable a safe operational stop of the robot. Pliz group introduced other attitude of safety in industry [46]. A camera system for three-dimensional safety monitoring, was developed in conjunction with DaimlerChrysler. Safety EYE locates in customized place, three-dimensional protective area around a danger zone with a single system. The areas can be detected and configured flexibly and quickly on a PC.

Similarly in the Team@work project, it was developed a 3D monitoring system to prevent humans and robots to have contact one with the other. [48] To detect the operator/robot positions three CCD cameras are applied, and send signals to the robot control unit to change its position and operating characteristics. [49], proposed another safety solution that consists of a camera mounted on the manipulator, an image processing with computer and a laser curtain that would change the real position of the robot.

2.25. Preventive solutions for the interaction levels 1, 2

Discussing of robot safety and autonomy degree completely depends on the capability to manage unexpected events occurrence, as failures or unforeseen environment changes. Fault handling and fault tolerant control should be considered as essential functionalities during safety interaction between humans and robots. [50] Reliability is depending on the capacity of the framework to manage with disappointments. In the paper [51] a model of failure categorization has been presented as an example. It should be mentioned that the picture of human robot interaction application is more complex. It is important to clearly define of the types of faults that can affect the robot to acceptable levels of robot reliability in HRI, and it should be considered during development and utilization.

In practice, preventing all possible occurrences is never fully attainable. During interaction, the robotic system should be monitored as to detect events or failures, recognize their location and type. A suitable Programming of the behavior robotic system, e.g., with different control strategies can be guaranteed for safe interaction and high tolerance collision preventing. During eventual collision with human, the robot should move as much as possible in a safe configuration. To examine the adapted techniques are suitable and sufficient, it needs a suitable analysis combination (e.g., FMECA, FTA) and evaluations (e.g., through stochastic modeling or experiments) to attained reliability.

2.26. Design with safety consideration

In order to diminish hazards severity it is useful to reduce manipulator link inertia and weigh which is achieved by redesign its mechanical characteristics.

Also, using light weight and stiff materials should be compliant with robot structure. (see Fig. 2.21 a-c) During impact occurrence the actuators' rotor inertia should be dynamically decoupled from the link which is needed the structure of robot arm adopted by soft covering with viscos-elastic materials or by adopting compliant transmission at the robot joints. [52] In approach stated in [53] the methodology of Distributed Macro-Mini actuation (DM2) was applied finalized to reduce inertia of manipulators arm. A pair of actuators is applied for each degree of freedom (joint) that are connected in parallel and placed in different parts on the manipulator.

Figure 2.21. Light weighted Arm design: a) KUKA, b) DENSO, c) DLRIII

Practical examination and experience show that for reducing hazard and risk strategy it is useful to utilize the effective design. The environment structured plays vital role beside mechanical redesign. Also, additional safety measures, planning and suitable system control is needed during safe and human friendly interaction. To ensure a safe interaction, robot should act in minimum danger motion and able to assess the level of danger in its current environment.

2.27. Visual and sensor monitoring with safety consideration

In order to increase the safety of interaction between human and robot and provide a feedback signal for robot actions, valuable information provided by monitoring of human actions is required. Mechanical forces and displacements are simplest way to monitor the situation during human robot interaction. Human monitoring communication signals is another class of monitoring systems. This system categories can be divided into physiological monitoring or into visual monitoring systems. An application where human intent can be read from a mechanical signal is in tasks where the robot can power-assist a human motion. For instance, Yamada et al. in [54] applied a Hidden Markov Model to the operator's purpose estimate from early motion of the human. Visual monitoring systems utilize camera tracking of the human in the interaction and use these data to guide the interaction [55], presented visual monitoring by user's eye gaze and head position. [56], provided hand gestures or facial appearance reading. Due to increase of safety, the human robot interaction in the workspace can be managed by stationary cameras. [57] Applied different image methods for detecting barrier of all robot motions. The robot motion changed their paths during detected collision. [58] Physiological response from person to person with large variability is an important problem.

Another one is that the same physiological signal is triggered for a range of psychological states; it can be difficult for a controller to determine which emotional state the subject is in, or whether the response was caused by an action of the system, or by an external stimulus.

2.28. Trajectory planning with safety consideration

In human robot collaboration safe control and trajectory planning are important, particularly if the environment contains additional obstacles. Whenever the level of potential danger could be minimize and satisfied goal it could be considered the planning of trajectory is safe. Various trajectory planning approaches have been proposed in the context, mostly based on heuristic variations or algorithms and artificial potential fields. [59] This approach does not require to search in the global path, it has the possibility to operate on-line, and easily modified sensor based on dynamic obstacles and trajectory planning. When the robot with redundancy is applied, this approach can be extended to allow the robot performing the task while preventing impact in the obstacles. They presented similar method when the trajectory goal and tasks are global location and special for redundant manipulator. In this method, obstacle avoidance generated the force and positioned the redundant manipulator to null space, so the robot can continue the goal trajectory while preventing impact against obstacles with redundant degree of freedom. The matter of this planning methods for robot is local search so the robot cannot reach to minimum of global location which is not optimize goal.

Another issue in the operational space is appalling forces during deriving the formulation. The requirement is to use the robot Jacobian to translate these forces to joint torques, and introduces position and velocity error near any robot singularities.

Currently industrial robots are position-controlled. Due to managing the successful execution of an interaction between human and robot accurately planning for task is required. For unstructured anthropic domains, such a detailed description of the environment is very difficult. As a result, pure motion control may cause the rise of undesired contact forces. In HRI the force/impedance control is important. The ability of sensing and controlling exchanged forces during collaboration tasks between robots and humans is essential.

The work [60] presented a robot manipulator under impedance control with an equivalent mass spring damper system, with the contact force as input (impedance may vary in the various task space directions, typically in a nonlinear and coupled way). The results obtained in a dynamic balance interaction systems between human and robot. The weight of human and robot structure influenced on the balance. Typically, the requirement of interaction tasks are precise value of contact force. The possibility to measure contact forces is provided by the robot with joint torque sensors. The integration of joint torque control with high performance actuation and lightweight composite structure, like for the DLRIII lightweight robot (see Figure. 2.22), can satisfy the requirements of safety and performance. The manipulator has possibility to move in near obstacles. [61] Also, in the work [61] the author uses mobile manipulator for path planning and measure the distance between the robot and any obstacle as a “safeness” in the cost function. Using genetic programming to generate path by multiple optimization criteria, including actuator torque minimization and distribution between joints, obstacle avoidance and manipulability.

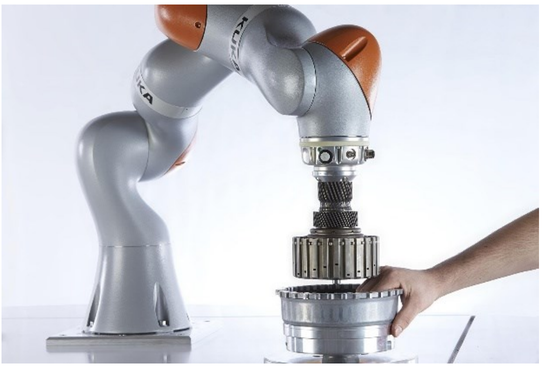

Figure 2.22: advanced robot kuka with high performance actuations

2.29. LBR iiwa perspective

With the LBR iiwa ("Leichtbauroboter"= lightweight robot, while "*iiwa*" is short for "intelligent industrial work assistant"), KUKA, as shown in Figure 2.23, will provide its customers with the means of implementing measures to minimize the risk of a HRC application in accordance with the standard (ISO 10218-1:2011) by means of a freely configurable safety controller.

This applies in particular to:

- Safe velocity monitoring
- Safe workspaces and safeguarded zones
- Safe collision detection (free collision)
- Safe force monitoring (crushing)
- Safe tool detection
- Safe switching of states in PL d and Cat. 3

Figure 2.23. Collaborative kuka robot

With the LBR iiwa, KUKA will provide the customer with the capability of implementing the risk assessment, also with regard to the forthcoming TS 15066. . Having high-precision sensors in each axis makes the robot manipulator very sensitive, and this contributes to increased safety and productivity. The considered robot's scheme and specifications are presented in Figure 2.24 and Table 2.3.

Side view

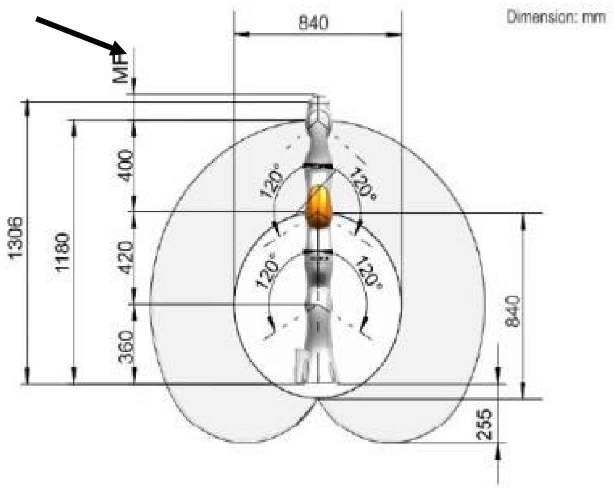

Figure 2.24. Technical specification.

Table 2.3. Technical specification

Range of Motion	A1	A2	A3	A4	A5	A6	A7
	± 170º	± 120º	± 170º	± 120º	± 170º	± 120º	± 170º
Speed with Rated Payload	±85º/s	±85º/s	±100º/s	±75º/s	±130º/s	±135º/s	±135º/s
Rated Payload	14 Kg		Repeatability (ISO 9283)			±0.15 mm	
Number of Axes	7		Axis-specific Torque Accuracy (of maximum torque)			±2%	
Wrist Variant	In-Line Wrist		Weight			29.5 Kg	
Mounting Flange A7	DIN ISO 9409-1-A50		Protection Rating of the Robot			IP54	
Installation Position	Any		Maximum reach			820 mm	

2.30. Ergonomics and recognition role in human robot interaction safety

There are many different ways to define and determine safety, effectiveness and reliability levels of task performance during interaction depending the particular role assignments.

Each Human Robot Interaction System could be defined as a Quintuple [62]:

HRIS= (T, U, R, E, I)

where T are the task requirements (cognitive and physical), *U= (C, P)* are the user characteristics (cognitive, physical), *R= (S, H*) are the robot characteristics (soft-, hardware), *E* describes environmental or ergonomic demands and *I* is a set of interactions.

The ability of human is very important to perform crucial mental tasks containing fundamental cognitive processes and functions. In order to increase the efficiency of human-robot interfaces, it is necessary to improve design of robotics cognitive by considering capabilities of human's cognitive in decision making, information processing and environment perception, etc. Unstructured information could make mistake and hazardous situation. Due to process of information, it is important to understand the human behavior depending on mental processing operations that human can perform at any time.

Human performance can be limited by time pressure, the amount of information that should be processed unit time, hazard, task complicity, etc. For example, the rate of data stream per unit time is consistent, around 1 bit/220 msec, if probably the operator surpasses this level, precision of the execution drops quickly [63]. In addition, mental capacity may be influenced by the need of involvement, data preparation, natural conditions, etc. Operator's mental workload will be influenced negatively by unpleasant situation. Cognitive (mental) over-burden is characterized as a distinction between the sums of assets accessible inside an individual and the sum of assets requested by the errand [64]. Hence, a quantifiable amount of the data preparing requests set on a person by an assignment, can lead to human hazardous behavior; this can be exceptionally risky amid HRI at a high level of the hazard. The possible causes of an unsafe human action are presented in the Figure 2.25.

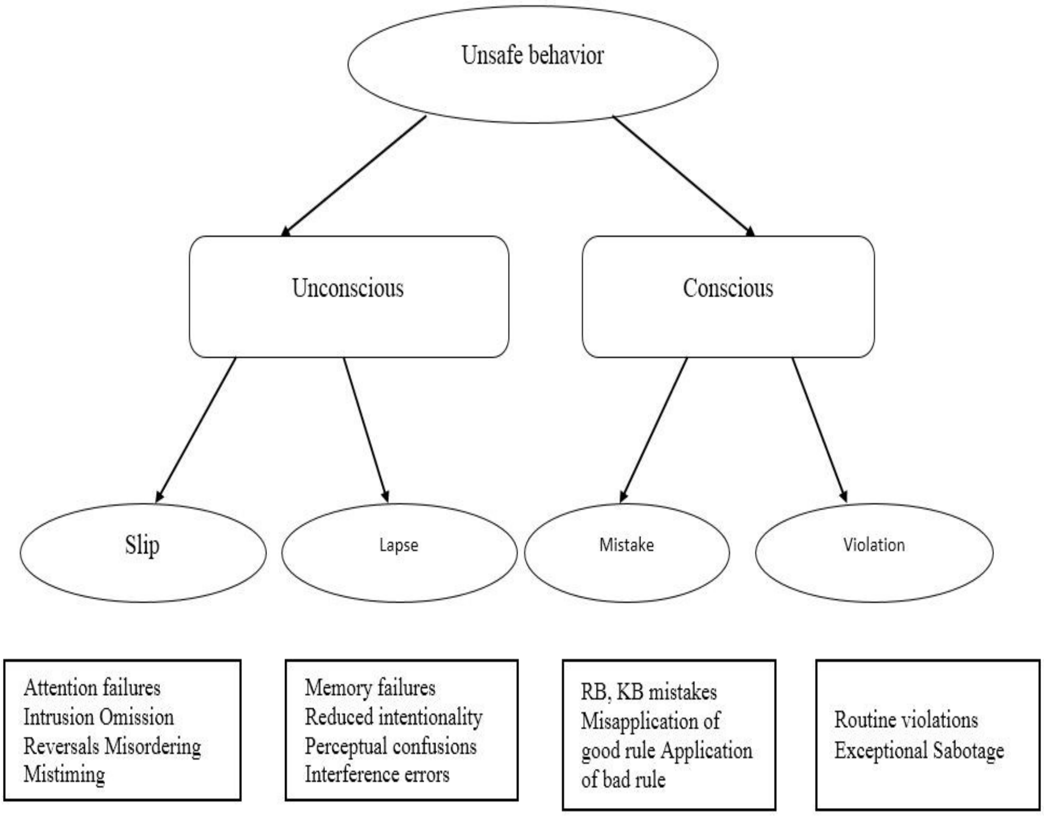

Figure 2.25. Unsafe behavior influencing factors schematic presentation

According to Rasmussen theory [65], the behavior of human can be divided in three classes as: skill-, rule-, and knowledge-based actions. The *skill-based* behavior denotes sensible performance without aware of control, it is a smooth, automated, and highly integrated patterns of behavior.

The rule-based is based on know-how awareness, when in different situation the rules could be misused, and the error happen when the incorrect rule or accurate one happen in the incorrect time. The knowledge-based behavior happen when the external indicator shortages the environment supporting such as: procedures, signs, or other sorts of shows that aid in making decisions. It might happen when there is ambiguous systems or an uncertainty in feedback, lack of control indication, false or erroneous procedures, inexperience or unavailability of systems, etc.

Thus, cognitive system design, human own experience, technical, skills, capabilities and nature itself can be categorized as main factors to influence on performance error free. The human factors of operators is usually less controllable although to solve the technical part ergonomic and safeguarding approach can be more controlled. In order to ergonomic analysis the human physical workload estimation can be applied. The research about anatomical, physiological features of humans in their working environment to optimize efficiency, health safety, and comfort has been meaning of ergonomics in traditionally. Due to benefit of human robot collaboration is need a new generation of ergonomics concepts to be introduced. The main idea of introduce robots into the human working environment is safe and effective collaboration with reliability and required degree of integration. An essential concept of ergonomic application is that workplace must be designed efficiency to meet body structure load and does not exceed the tolerance border.

When ergonomic rules are applied into robotics, human-centered work space should be design regarding to characteristics of robot specification and improve work with considering increase efficiency and performance and eliminate human's health hazard. Many factors cause human error such as poor organization of work, insufficiency in tasks distribution, faulty spatial arrangements, inadequate control panel layout, ambiguity in elements functionality, etc. it is essential to design effective sharing task between humans and robots to optimize the collaboration, release humans from excessive loads (mental, muscular), accelerate the performance, etc.

In the handbook published by S. Nof [66], in order to understand if either human or robot can complete a given task, the charts related Human-Robot ability have been proposed, each of them makes reference to one of the three main characteristic categories: physical skills, mental and communicative capabilities, and energy consumption demands. The spatial dimensions, strength and power, consistency, overload performance, and environmental characteristics are belonging to first chart. The second chart is dedicated to the communicative skills and mental requirements, at the end the chart refers to virtual evaluations of robot and human energy and power characteristics. The psychological needs of the operator are provided in ergonomic guidelines.

As mentioned by psychological studies carried out and reported in [67], [68], the most errors and constraints are identified according to different collaborative tasks with robots as following: high sensitivity to the ambient working conditions (noise, vibration, humidity, workplace dimension); fear and panic to robot abrupt, unexpected, nosy and fast movements; perception and reaction are highly dependent on the current physical, emotional state of the individual; misunderstanding of the robot's actual state (halt, mute); misestimating of the robot speed, distance to hazard (underestimation of large distances and overestimation of the short); faulty hazard recognition; failure to prompt respond to a recognized hazard; misperception of the direction of a robot arm movement; loss of attention; reluctance to safety instructions maintenance; irrational response in emergency conditions, etc.

According to studies provided by Nagamachi in [69], the different distances of themselves and speeds of robot with respect to the safety condition interaction was tested. The optimal distance and speed are provided with 225 mm and 300 mm/s. the better sense is received by environment control is the optimal area for human visual modality, as mentioned in ergonomic guidance [64]. The desirable observation area is 45° angle of vision, however the outside of this space causes to increase the reaction time.

2.31. Conclusion

In this chapter, firstly, the background of robot hazards for operators, and robot accident origins have been discussed. Then, complete description about safety standards and regulations of applying robot have been presented. At the next step, technical specifications related to four different scenarios for increasing safety of industrial collaborative robot were discussed. These methods are Safety-rated Monitored Stop (SMS), Hand-Guiding operation (HG), Speed & Separation Monitoring (SSM) and Power & Force Limiting (PFL). At the next step, risk assessment for the collaborative environment has been discussed and specifications of the collaborative robot has been described.

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Chapter 3

AHP method and HTA

3.1. Introduction

The Analytic Hierarchy Process (AHP) is considered as a one the primary methods of decision making; through the decision making process there is the possibility to select the best alternatives regarding to various criteria. This method begins with performing pairwise comparison judgment along the alternatives and ends with determining the overall ranking of the alternative with respect to different criteria. AHP method is not only capable of regarding inconsistency in decision making process but also it suggests solution to improve the consistency in the analyses.

AHP would be structured hierarchically and in three levels [1] :

The top level is the goal of the decision making process; the second level includes the considered criteria and the third level consist of the available alternatives as shown in Figure 3.1 . At first glance the application of the hierarchal approach to complex systems seems to be a challenging task, however if all parameters are properly organized this method results to be an effective, simple method. Complex systems should be decomposed into different levels from top to lower levels hierarchically; in each level the respected elements and parameters should be considered. As soon as the general framework of the structure is constituted, AHP will be a very effective method to apply to the system.

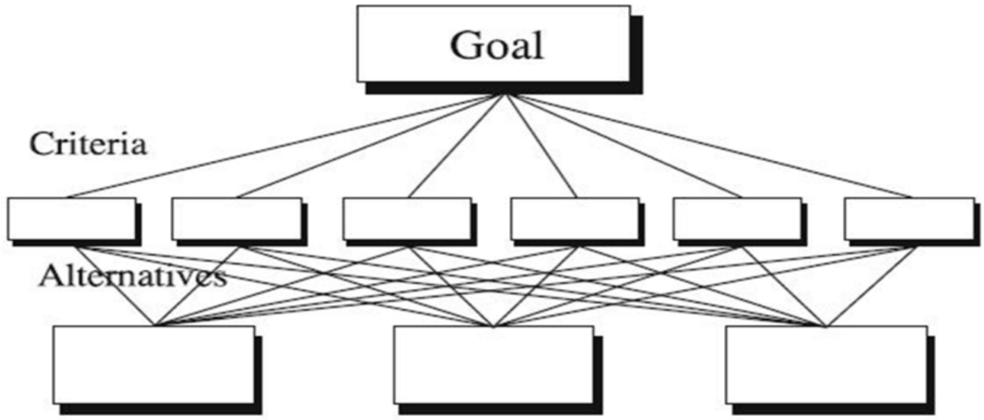

Figure 3.1. Decision algorithm for solving a problem

The most important factor through the constitution of the hierarchal diagram are the necessary parameters. These details should not be so superficial that one cannot decide based on that neither so broad that eliminate the sensitivity of the involved elements.

Decomposing the main goal and the sub-level goals not only frames the general view of the complicate analysis but also gives us the clear view about how to judge about the alternatives.

The hierarchy diagram elements should be consistent to each other, however there is a high possibility that one element does not play the role as a criterion for all the sub-level elements. The hierarchy may have sub-hierarchies which are connected by the topmost elements.

Depending on the importance of the elements, they may contain general or specific details to organize the priorities of the task, criteria, sub-criteria and the alternatives' properties should be compared separately with respect to the next higher level elements.

Lastly, having studied all elements importance, priorities and effects on the main task, elements with lower value of the importance index are ignored.

3.2. Description of AHP procedure

Performing discrete and continue paired comparison of elements in the hierarchy diagram, AHP is capable of obtaining the general ratio scale. These measurements may be according to the real data measurements or based on the desired strength of preferences scale. Having a comparison among the physical and psychological subjects or in other words among the tangible and intangible subjects is quite a challenging issue; however AHP proposes a method to have a trade-off between these subjects.

Analytic Hierarchy Process is a nonlinear method capable of solving the deductive and inductive problems without the need of syllogism [1]. In other words, this method considers various factors' effects simultaneously and gives a final numerical values for these comparisons. The difference of linear and non-linear hierarchy is shown in Figure 3.2 This method has a wide range of applications in multi-criteria decision making, objectives planning and in conflict resolution [2, 3].

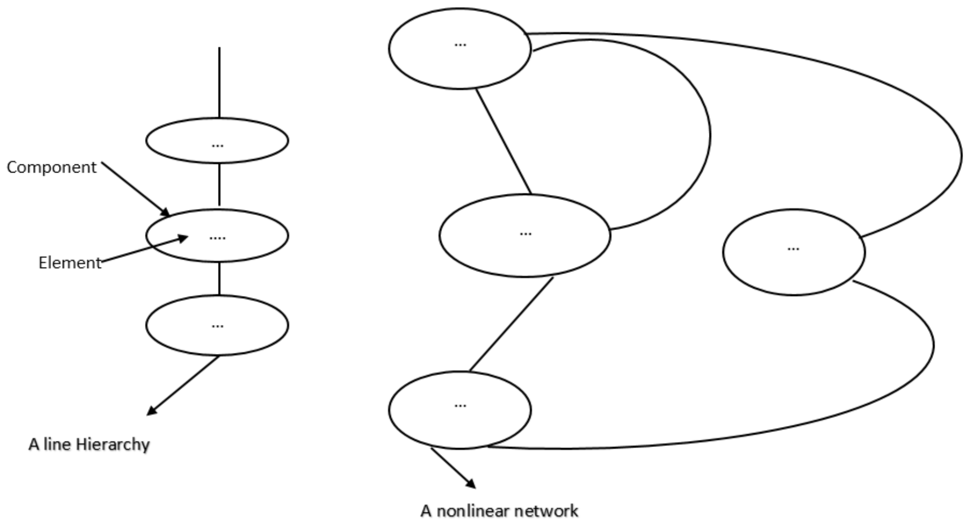

Figure 3.2. Linear and non-linear hierarchies

In AHP method, as mentioned before, in order to determine the ratio scale of the involved elements it is necessary to perform the pair-wise comparison among the elements. While in discrete base problems this comparison among the elements leads to a dominance matrices, in continuous base problems it results into kernels of Fredholm Operators [4] and the ratio scales are obtained in the form of eigenvectors. These matrices and kernels are positive and reciprocal vectors (for instance, $a_{ij} = 1/ a_{ji}$). In the case of a diverse judgments, many works have been done to characterize these matrices and facilitate the process of synthesizing group judgments [2, 5,6].

Shortly, the main principles of AHP are as following [6]:

1) Mutual relation
2) Consistence elements comparison
3) Hierarchic dependence along with expectations of the rank validity
4) Outcome value and dependence on the structure

3.2.1. Absolute vs. relative measurement

There are two kinds of comparisons; absolute and relative. In absolute comparison, alternatives are compared with respect to the baseline while, for relative comparison, pair-wise comparison of alternatives should be done. AHP is capable of handling the both types.

Relative measurement is obtained from the ratio scale of element values compared pair-wisely, for example, if the two element values are W_i and W_j the pair-wise ratio is W_i/W_j. However, absolute measurement has been done based on the alternative ranks regarding to the criteria intensities; for example one may classify the alternative ranks as excellent, very good, good, average, below average, poor, and very poor and may express them with words or with grades A, B, C, D, E, F, and G.

Having set the priorities for all criteria, pair-wise comparison has to be made among the relative rating to determine the ideal intensity by dividing each priority by the largest rated intensity.

At the last step, the rank of each alternative is determined by calculating its ratings related to all criteria and the summation of them are reported. The ratio scale value for all alternatives should be reported in a normalized format by dividing each value by the total value.

3.2.2. Fundamental scale definition

As mentioned before, in AHP method compatible elements pairs are imposed to the pair-wise comparison judgment [1]. The values fundamental scale representing the judgment intensities is shown at Table 3.1. These scales demonstrate the effectiveness of the alternatives. Someone may think that this type of measurement, in comparison with the numerical method, would be insufficient in case of determining the exact proportion of the elements value but this problem can be solved easily. In other words, for example if we want to report the element value proportion which should be between 1 and 2 as 1.2, someone may think that it is impossible to use descriptive values. Having defined wide range of verbal scales (such as very strongly more, extremely more, etc.) will solve this problem as shown at Table 3.1.

Table 3.1. The fundamental scale

Intensity of importance	Definition	Explanation
1	Equal importance	Two activities contribute equally to the objective
2	Weak	Experience and judgment slightly favor one activity over another
3	Moderate	
4	Moderate plus	Experience and judgment strongly favor one activity over another
5	Strong importance	
6	Strong plus	An activity is favored very strongly over another; its dominance is demonstrated in practice
7	Very strong or demonstrated Importance	
8	Very, very strong	The evidence favoring one activity over another is of the highest possible order of affirmation
9	Extreme importance	
Reciprocals of above	If activity i has one of the above nonzero numbers assigned to it when compared with activity j, then j has the reciprocal value when compared with i	A reasonable assumption

Rationales	Ratios arising from the scale	If consistency were to be forced by obtaining n numerical values to span the matrix

3.2.3. Cost Analysis in hierarchy structure

Usually hierarchy method is used to perform the benefit analysis for finding the best alternatives, however in many cases it is essential to do cost analysis with respect to the desired alternatives. A parallel analysis performance facilitates obtaining the benefit-to-cost ratio (based on the defined criteria) which will clarify the optimum solution.

3.2.4. Defining eigenvector for weights and consistency

Different methods are available to derive the priorities vector from the matrixes constituted from the ratio scales (a_{ij}). But emphasis on consistency of priorities will result into the eigenvalue formulation of Aw = nw [7].

If the priorities based on a single criterion are shown by $w = (w_1,\dots,w_n)$; by multiplying the comparisons ratio matrix to w, nw is obtained as following:

$$\begin{pmatrix} \frac{w_1}{w_1} & \frac{w_1}{w_2} & \cdots & \frac{w_1}{w_n} \\ \frac{w_2}{w_1} & \frac{w_2}{w_2} & \cdots & \frac{w_2}{w_n} \\ \vdots & \vdots & \ddots & \vdots \\ \frac{w_n}{w_1} & \frac{w_n}{w_2} & \cdots & \frac{w_n}{w_n} \end{pmatrix} \begin{pmatrix} w_1 \\ w_2 \\ \vdots \\ w_n \end{pmatrix} = n \begin{pmatrix} w_1 \\ w_2 \\ \vdots \\ w_n \end{pmatrix} \qquad \text{Eq: (1)}$$

If the measurement process or devices are not accurate enough to calculate the exact value of the priorities proportion (w_i / w_j), this value should be estimated; in this way Aw is equal to $\lambda_{max}w$ where λ_{max} is the largest or principal eigenvalue of A' = (a'$_{ij}$) and A is the pair-wise comparison matrix. It is important to mention that a_{ij} is representative of the importance of alternative i over alternative j.

Having increased the matrix to a large power, the priority vector of $w = (w_1,\dots, w_n)$ is calculated by summing over the matrix rows and normalizing them. As soon as the difference between priority vector components of the *k*th and the (*k+1*)th power becomes less than a predefined value, the raising of the matrix power is stopped. The priorities vector is the derived scale along with the comparisons matrix.

In order to obtain the value of the principal eigenvalue λ_{max} , when there is an estimation of *w* available, in normalized format is to add the columns of A matrix and multiply the result by the priority vector *w*.

It is necessary to compute the error caused by the inconsistency in matrix A; this estimation will results in improving the consistency of the judgments.

The consistency index CI of the comparison matrix is calculated according to the following equation:

$$C.I. = (\lambda_{max} - n) / (n - 1) \tag{2}$$

The consistency ratio (C.R.) results from the comparison of the consistency index with one of the values presented at Table 3.2. These values are presenting an average of the random consistency index. Preforming this procedure, a consistency index for the AHP hierarchy will be obtained. A value of 10 percent or less expresses that the adjustment is small enough in comparison with the eigenvector entries values, while a value larger than 10 percent indicates the need for revising of the judgments.

Table 3.2. Average random consistency (RI)

Size of matrix	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
Random consistency	0	0	0.58	0.9	1.12	1.24	1.32	1.45	1.49

3.3. Constitution of a hierarchy structure

Depending on the nature of the problem, hierarchy structures can be made in different ways; however one should have always in mind that the highest and lowest elements, which are used to constitute the hierarchy, should be always matched and comparable.

In order to constitute the hierarchy structure the following steps should be proceeded:

1. Determining the overall goal.
2. Determining sub-goals of the overall goal.
3. Identifying the criteria which should be satisfied to accomplish the sub-goals.

4. Classifying the sub-criteria of each criterion and presenting them in terms of parameters values or verbal intensities.
5. Identifying actors involved.
6. Identifying actor goals.
7. Identifying actor policies.

3.3.1. Task analysis background

HTA has been introduced as "best known task analysis technique" based on the research published by KIRWAN and AINSWORTH [8]. While this method has been used firstly in ergonomics areas, the origin of all task analysis methods results from some scientific management movement in 1900s [9,10].

Frank and Lillian Gilbreth [11] searched for a method to improve the task analysis; their method was based on principles which had to break down and each task elements should be studied separately. In their method, each individual element was reported against the time so they called it 'time-and-motion' study [11]. While for example, the main focus of this method was according to individual elements related to physical movement of a task, some cognitive elements such as 'search, 'select' and 'find' during performing the task were ignored. This defect of the method was reported by [12]. Annett has criticized the HTA method in 1996 with some serious questions; he believed that HTA not only has to describe what will happen during the procedure but also should be capable of describing how the procedure has to be done or what are the wrong scenarios.

The scientific management approach presented previously was not capable of considering psychological aspects of the tasks [13].

Annet [12] has pointed out a group of influences which have contributed to the previously presented HTA. He mentioned the few influences as following:

Tasks decomposition into their elements, human performance questioning in systems, determining physical and cognitive activities, representing of the analysis in a graphical manner, constructing the theory for human behavior.

However, one of the most significant concepts of HTA was the error variance identification in system performance [14]. It has been reported by Annet [15] that identifying and dealing with factors generating the largest error variance have been captured through the top-down systems approach of HTA. Theses error variance may result from humans, machines or the interaction between them.

3.3.2. Principles of hierarchical task analysis

According to Annet et. al [16], the primary approach for applying HTA was based on a theory of human performance. The performance toward a main goal may be presented through multiple analysis levels.

The three main principles constituting the analysis are as following:

First principle:

At the highest level of hierarchy, a task including of a process defined in terms of its goal is considered. In other words, the goal is indicating the overall objective of the system with respect different criteria and HTA describes a system with respect to its goals.

Second principle:

Decomposition of sub-operations in a hierarchy format can be done in HTA; these sub-operations should be presented in terms of sub-goals which they will be presented in terms of measurable performance criteria.

Third principle:

There is a hierarchical relationship between the goals and sub-goals; this means that in order to satisfy the goal, sub-goals have to be satisfied.

Progressive hierarchy analysis could go on continually, [16] mentioned that knowing when to stop the analysis is quite challenging process. One method to predict the stopping procedure of the analysis is according to P*C rule. Based on this rule, P is the probability of failure and C is the cost of failure: as soon as the value of P multiply by C reaches a predefined acceptable value the analysis should be stopped. However in many situations the probability and cost of the failure are unknown and still there is a problem to determine when to stop the analysis [17]. Piso in his published work [18] proposed a method which was less complicated and time-consuming. He proposed that instead of predicting the stopping period of the hierarchy analysis based on probabilities and costs of failure, it is possible to keep on the analysis until the sub-goals are clear to decision makers.

3.3.3. General framework for development of hierarchical task analysis

In the following the list of the steps needed to perform a HTA:

a) Define the purpose of the analysis

Different purposes of the HTA may include of system or interface design, operating procedures design, analysis of workload and manning levels, training design and developing person specifications.

b) Define the boundaries of the system description

The boundaries of the system could be different based on the respective purpose; if the system constituted from an individual or group of people then the entire set of the individual or group of people should be analyzed.

c) Access to a wide range of system information sources

All researchers who have worked with task analysis methods, insisted on the importance of system information sources used to improve and check the accuracy of the HTA [15,19-21]. Different sources such as observation, operating manuals, interviews and simulations can be used to check the accuracy and validity of the hierarchy analysis.

d) Describe the goals and sub-goals of the system

Decomposing the goals will generate new operations needed to define sub-goals for each of them. However, it is worth mentioning that the sub-goals are being described not the operations [16] and these sub-goals should be representative of their higher level goals [19].

e) It is better to not allocate more than 10 sub-goals to a super-ordinate goal.

It is recommended that not to increase the number of sub-goals more than 10 but if there are more than 10 sub-goals it is necessary to combined them to together under another sub-ordinate.

f) Sub-goals should be in connection with goals under predefined conditions.

Plans help the analyst to define the required conditions for defining sub-goals. They could be classified into the following groups [21]:

- Fixed sequences
- Contingent sequences
- Choices
- Optional completion
- Concurrent operations
- Concurrent cycles
- Sub-goals are generated from the plans that include particular context. These context may consist of time, completion of other sub-goals,

environmental conditions, system state and receipt of information. The analyst should investigate about the generation of each goal sub-ordinates during the analysis. It is worth mentioning that the exiting condition of the analysis should be determined precisely, otherwise the analysis would stuck in a closed loop.

g) Immediately ignore re-describing of sub-goals when the hierarchy is clear enough to satisfy the task. Although the stopping rule has been presented before but since it is just a rough approximation, the analyst should determine if the hierarchy is good enough to fulfill the task.
h) Verify the analysis with other experts; it helps to double check the analysis to find the possible problems [15].
i) The analysis should be always ready to change and develop since there is always possibility of changing plans and sub-goals.

Generally HTA can be presented in three main different formats; hierarchical diagrams, hierarchical lists and the tabular format.

3.3.4. Applications of hierarchical task analysis

Hierarchical Task Analysis (HTA) has been used over thirty years; this method has been firstly used as a determining training requirements tool but now has diverse applications. Nowadays this method has been widely used in job aid design, error prediction, interface design and evaluation, allocation of function and workload assessment.

Flexibility of HTA made this method as a popular method which can be used in almost all tasks. However, the major application of HTA is in ergonomic field [20]. This method has been presented as a cost saving approach in which there is no need to continually re-design all tasks of the analysis, however there is not a single template of HTA which can be used for all applications [15].

During HTA analysis not only the main goal will be analyzed in detail, but also it helps the decision makers to investigate about challenges of human interaction with the respective system. In other words, HTA may reveal some unknown aspects of the procedure and highlights the incompatible elements of the analysis for analysts and decision makers; so they can improve the efficiency of the design. The general applications of HTA from ergonomics texts have been collected and reported by [22] as shown at Table 3.3.

Table 3.3. Application of HTA from ergonomics texts

Application	Kirwan & Ainsworth (1992)	Wilson & Corlett (1995)	Stanton (1996)	Annett & Stanton (2000)	Shepherd (2001)
Interface evaluation	✓	✓	✓		✓
Training	✓	✓	✓	✓	✓
Allocation of function	✓	✓		✓	
Job description	✓		✓	✓	✓
Interface design	✓	✓	✓	✓	✓
Work organization	✓	✓	✓		✓
Manuals design	✓	✓	✓		✓
Job aid design	✓	✓	✓		✓
Error analysis	✓	✓	✓	✓	
Error prediction	✓	✓	✓	✓	
Team task analysis					✓
Workload assessment			✓	✓	✓
Procedure design			✓		✓

3.4. Conclusion

In this chapter, the two main decision making methods and their applications which are used in this thesis have been introduced and discussed. Analytic Hierarchy Process (AHP) as the primary decision making tool has been described; this method is capable of choosing the best alternatives with respect to comparison between different criteria. The methodology for constituting the framework of other decision making method, Hierarchal Task Analysis (HTA), has been described completely; this method is a very powerful tool for performing tasks decomposition and allocation for a system.

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Chapter 4

Methodology

4.1. Introduction

It is evident that incorrect or inadequate workplace design and operation will have negative effects on working capability and result in low productivity and have direct negative impacts on human's health and safety. Thus, a comprehensive knowledge about possible hazards, potential risks and protective procedures can significantly contribute to the successful planning of manual working cells and workspaces. This chapter discusses the methodology that is aimed to provide a comprehensive analysis of collaborative tasks between human and robot in a collaboration environment. The goal of this methodology is to provide safe collaboration between human and robot in the assembly line of automotive industry.

Applying robot as assistance needs special knowledge and comprehensive analyses to optimize implementation. In this research as presented in figure 4.1, at the first step, decision makers discuss about advantages, disadvantages, risks and hazards of human collaboration with robot.

In the second step, decision makers according to AHP method decide to utilize robot beside human during complete tasks by providing a safe environment. In the third step, systematic risk assessment including the overall process risk analysis, risk estimation, and risk evaluation is applied. Risks can be assessed at an organizational level or a departmental level for projects, individual activities, or specific task risks. Different tools and techniques may be appropriate in different situations. Risk assessment provides an understanding of risks, their causes, consequences, and their probabilities. Risk assessment provides decision-makers and responsible parties with an improved understanding of risks that could affect achievement of objectives and the adequacy and effectiveness of controls already in place. This provides a basis for decisions about the most appropriate approach to be used to treat the risks. The output of risk assessment is an input to the decision-making processes of the organization. Risk assessment is started with task–based risk analysis which analyzes the task and identifies the task associated with hazards with respect to reference of the safety standards, guidance and the risk category based on the interaction levels differentiation. In the fourth step, HTA method is applied to determine tasks between robot and human. In the following steps of risk analysis and risk assessment containing hazard identification, risk estimation, risk evaluation and safety requirement will be describedduring installation. Then the next step contains simulation part modeling different scenario of the collaboration between human and robot during assembly of parts. At the last step, the sequence of activity is run in the real collaboration scenario in the laboratory environment to validate the collaboration.

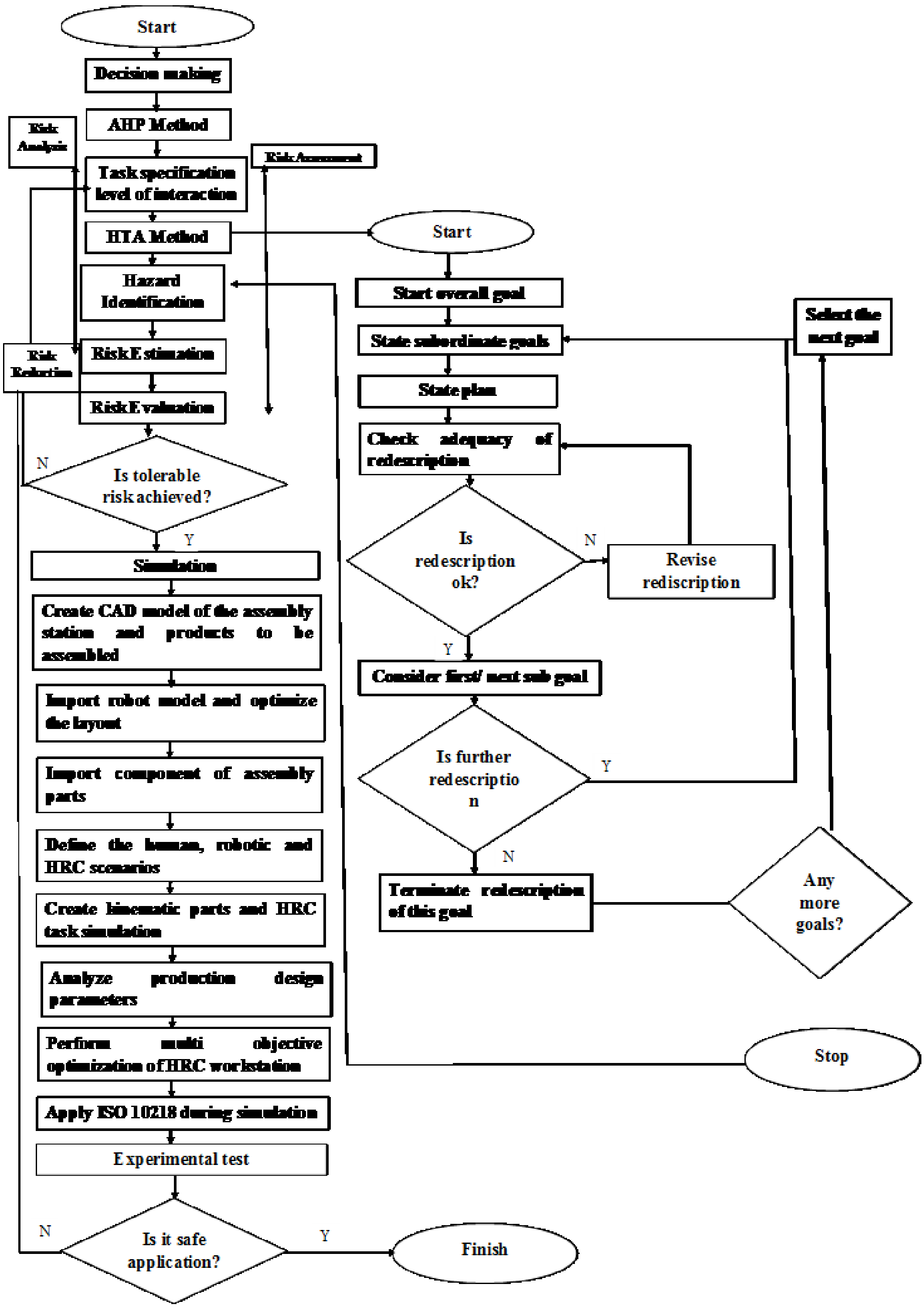

Figure 4.1. Methodology overview

4.2. AHP

Evaluating the efficiency of a process qualitatively with respect to various criteria for finding the optimum solution is not an easy task; however, using quantitative analysis, such as the analytic hierarchy process (AHP) [1,2], provides a good solution to satisfy this desired objective. In our research as presented in figure 4.2, the desired goal is to assemble components with respect to productivity, quality, safety and human fatigue. AHP analysis as an evaluation methodology has been used to compare a human-only system and human-robot collaboration system.

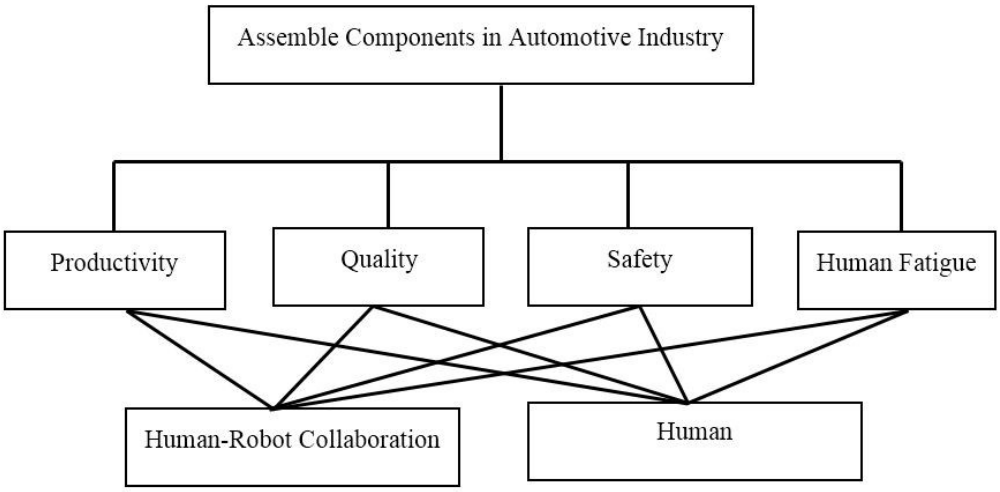

Figure 4.2. AHP analysis overview for assembling components in automotive industry.

To implement this activity, three expert personnels participated in decision-making and planning, and they support the author's choice of the AHP method to evaluate the efficiency of the human-robot collaboration.

The AHP analysis proposed by References [3–7] is defined in eight general steps, as follows:

- Identify the problem and define the goals.
- Construct the general framework of the AHP analysis in a hierarchically descending order; this means that the objective set at the highest level is followed by the criteria set at the intermediate levels, and then solutions, which are set at the lowest levels.
- Use the pair-wise comparison scale for AHP preference from References [3–7], ranging from 1–9 (intensity of importance) as shown in Table 4.1. In this scale, 1 expresses the equally-preferred status and 9 expresses the extremely-preferred status.
- Construct the pair-wise comparison matrix for the four criteria.

- Construct the pair-wise comparison matrices of alternatives for each specific criterion; this means that if there are n criteria and m alternatives available in the procedure, there should be n matrices with the size of m × m.
- Construct the synthesized comparison matrices of alternatives for each specific criterion to calculate the priority vectors; each value of the synthesized matrix is calculated by dividing the same element in the summation of its column. Each priority vector is then calculated as the average of the new matrix row.
- Calculate the consistency ratio for the pair-wise matrix of the four criteria to check the consistency of the analysis comparisons.
- Construct the priority matrix of alternatives (solutions).

Table 4.1. Average random consistency (RI).

Size of matrix	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
Random consistency	0	0	0.58	0.9	1.12	1.24	1.32	1.45	1.49

4.3. Task Analysis

4.3.1. Levels of Interaction for Human-Robotic Collaboration

The differentiation of interaction levels during human-robot collaboration is the main concept of tasks analysis. To identify the task and the method of collaboration between human and robot 4 levels of interaction are suggested, where each level of interaction needs different approaches to provide safety, safeguarding means installation, safety criteria application, compliance with different safety requirements, etc. Table 4.2 demonstrates these arrangements.

Table 4.2. Levels of Interaction for Human-Robotic Collaboration

Interaction Distance	Description	Human Task
L1	Inside the robot operational work space (physical contact)	Guiding
L2	Outside the operational zone, within immediate space in the restricted one (in close vicinity)	Teaching Assembling
L3	In safeguard space, within the arm maximal reach	Verification Monitoring
L4	Outside the robot maximal reach	Observing

The level (L1) represents tasks in a shared workspace in which the physical contact between the robot and operator is allowed. Level (L2) represents the tasks in which the operator is separated from the robot based on different task allocation or control strategy. Although the operator may work in a close distance with robot and authorize to enter to workspace while he is monitored by safeguards but he is not allowed to enter the robot operating zone. In level (L3) the operator is placed in a larger distance with robot; however, he may be within the reach zone of the robot's arm and huge precautious is needed. In level L4, the human is working completely outside the robot zone, however, there is still some hazards from the possible thrown objects in robot working space.

In other words, these levels determine the operator severe injury probability in which the L1 is the most dangerous zone and the L4 is the least dangerous zone for the operator. During each procedure, the injury probability of every interaction level is determined and the proper method to deal with different levels will be selected from Table 4.2 The schematic of these levels is indicated in Figure 4.3.

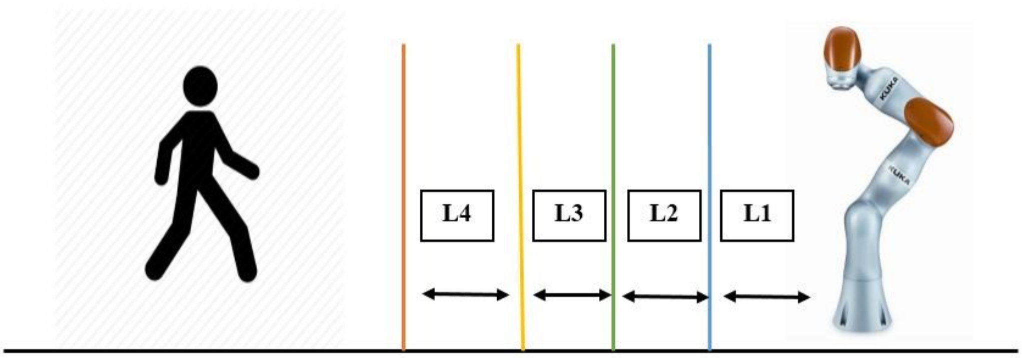

Figure 4.3. Interaction levels in collaboration workspace.

4.3.2. HTA

There are various methods available for analysis of the operation tasks. These methodologies include the hierarchal task analysis (HTA), goal-directed task analysis, and cognitive tasks that are used to model human-robot interactions [8]. The HTA method is a scientific method used for determining human tasks, regarding different ergonomics and human factors [9]. HTA has numerous applications in different areas, such as entertainment, police and military, space exploration, manufacturing, and mining and agriculture [10]. In order to constitute the HTA diagram, all tasks should be defined as goals and sub-goals; they all must be completed to achieve the final goal [11]. In this specific study of human-robot collaboration, HTA [12-14] would be a very effective method to determine the collaborative tasks between humans and robots.

Flexible approach should be used to construct the HTA, since probably a number of iterations are needed to achieve the main sub-goal. The number of iterations depends on the complexity timing procedure of the analysis; for simple analysis three iterations are needed while, for complex analysis the number may increase up to 10 iterations.

The overall procedure of constructing the hierarchal framework was described before in chapter 3 in 3.1.7 and 3.2.2 sections. The development procedure of the hierarchy is shown at Figure 4.4; however, this figure just consists of the steps “d” to “f” related to decomposing tasks to achieve the main goal.

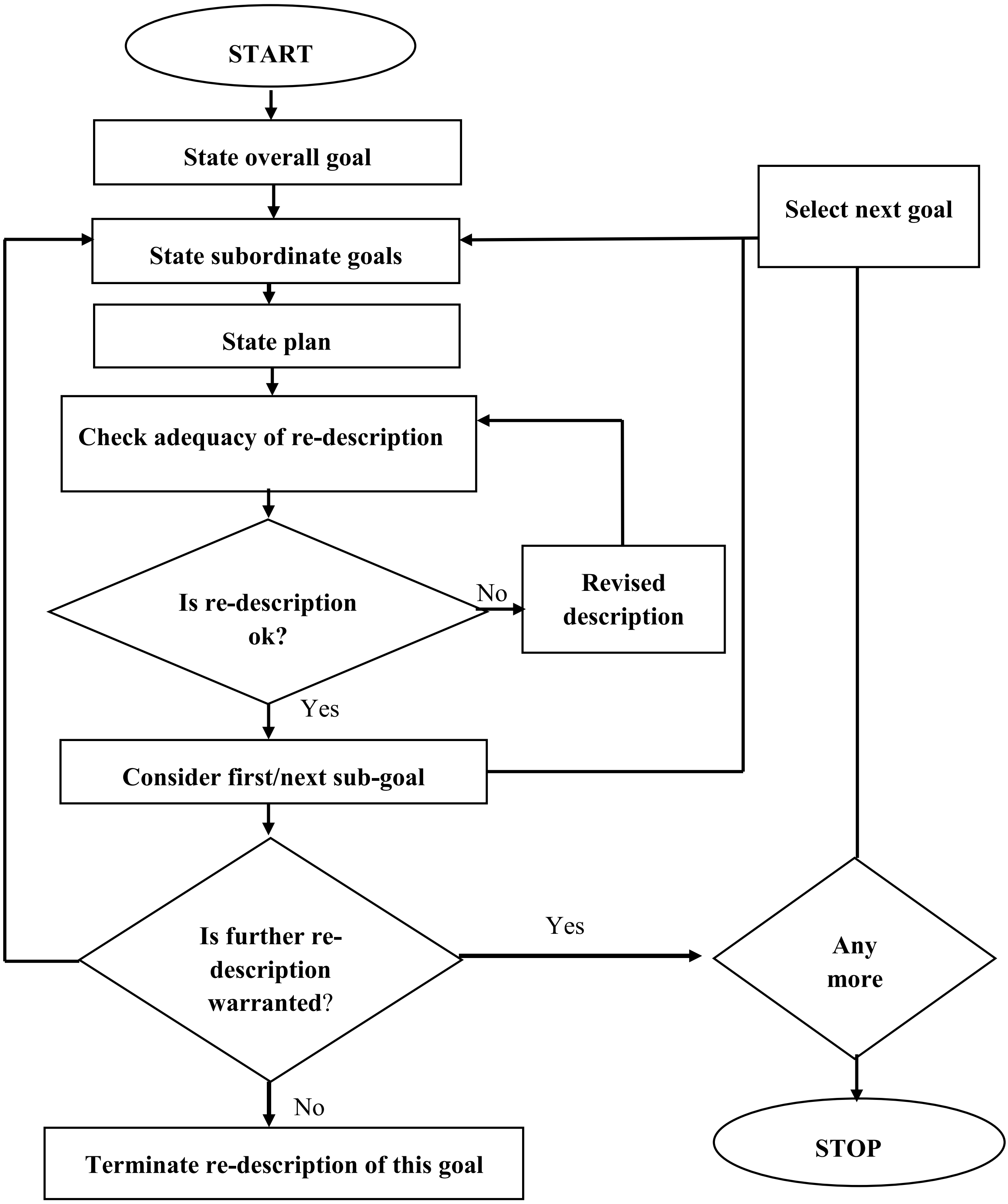

Figure 4.4. The overall procedure of constructing the hierarchal framework

4.3.3. Hazard Identification

Task along with danger relies on important parameters such as task specification, application of robot and the interaction level. The reliable system should be provided by the necessary information prepared from the experts. These information would be related to the interaction level specification, task procedure time, robot type and its characteristics, manipulating equipment and the workplace size. These information are saved in the system data base along with the respective standards of safety and ergonomics.

During the system assessment hazards are classified into three main categories: ergonomic, cognitive and mechanical or electronical hazards. All the interaction levels are associated with their own hazards; these hazards depend on the human-robot interaction procedure, human-robot collaboration distance, the operator duty and the task specification. However, physical and cognitive parameters should be considered too; if performing a task needs a lot of physical and mental effort, this will increase the risk of errors which results in hazard appearance. The result of the assessment is presented as a list of the task related to hazards specifications. This list consists of the potential hazards, causes of them and their consequences as shown at Table 4.3.

Table 4.3. List of the main hazards, causes and consequences

Hazard	Task / Factor	Description	Causes / consequences
Mechanical / Electrical	Welding, Painting, Cutting, Assembling, Drilling, Milling	Crushing Trapping Collision Stored energy Rejection Electrical choke Burn Poisoning Pressure Shearing Cutting Severing	***Cause***: Failure of Robot parts, Instrument failure, Human error, Failure of control, Software Failure, Firmware failure, Safeguarding failure, Incorrect work planning, task design, Incorrect task sharing. Incorrect time process scheduling, inadequate installation, usage. ***Consequence***: Robot (part) sudden movements. Unintended movement of associated machines.

			Unintended start up. Instrument erroneous action, Unexpected release of potential energy from stored sources, high pressure fluid/gas injection or Ejection, Contact with live parts or connections.
Ergonomic	If any indication from the *Tab. 3.6* (left column); Insufficiency for the Factors: E1- E5, E8 (*from Tab.3.10)*	Strain/Pain Physical fatigue Hearing loss Visual Loss Risk Wrong Protection	***Cause***: Excessive Physical Load, Inadequate TP design (E1, E2), Insufficient work cell design (E4), Poor GUI Design (E3), Incorrect work conditions (E5), Wrong task distribution (E8), Inefficient work planning, failure of Robot parts, other Machinery, Faulty design, installation, usage, spatial arrangements, Safety Features Insufficiency ***Consequence****:* Erroneous task performance, Risk Taking behavior, Elevated noise level, and long term exposure. Effect on the hearing and balance, awareness, speech communication, perception of acoustic signals, vigilance, Insufficient lighting, Visual Awareness loss, High Hazard Exposure, Risk Likelihood.

Cognitive	If any Indication from the *Tab. 3.6* (right column); Insufficiency for the Factors: E2, E3, E5, E8 (*from Tab.3.10*)	Fear/Anxiety Mental fatigue Stress	***Cause***: Personnel Hazard Perception, Excessive task cognitive load, Poor Control Panel Design (E2), Poorly designed user interface (E3), Bad work Conditions (E5),Incorrect task distribution (E8) ***Consequence****:* Unsafe behavior, Erroneous work, Task misunderstanding, misuse, recognition of Hazards and hazardous situations is obscured, erroneous work, unsafe behavior.

4.3.4. Risk Assessment Algorithm

Having identified the possible hazards of the system, they should be studied with respect to their probability and severity. Generally the main goal of performing risk assessment is to gather enough information about the hazards of the system and constitute the characteristics of the system safety design. Different data should be provided to perform the accurate risk assessment; these information might include of application of robot, structure and function of robot, the workplace information and the operator would work with robot as presented in Figure 4.5.

Risk assessment during a human-robot collaboration application based on ergonomic (E) and personnel (P) characteristics. As soon as the affecting factors reach the value below the predetermined standard value, these factors may cause a huge danger which will be reproduced in the hazard identification output.

Generally, valuable information about the existing risks which could jeopardize the accomplishment of the system objectives and the effectiveness means of system control can be obtained for decision makers. In this way, an appropriate approach for interacting with the possible system risks will be constructed. The final output of the risk assessment would be considered as an input to fulfill the decision-making processes of system. On the other hand, risk analysis obtaining a good understanding of the risk concept will produce an input for the risk assessment and helps the decision makers to decide whether there is a need to consider the risk or not; also it will clarify the appropriate strategy to deal with the respective risk in each step. Risk analysis including consequences and probabilities of the identified risks will determine the effectiveness of the system control means. Risk analysis deal with risks sources consideration, risk consequences and the probability of the risk occurrence. In this way, it is necessary to identify the parameters which can affect the consequences and probabilities of the risks.

Having considered risk control means and their efficiency, it might be essential to use various techniques for complicated applications. Risk analysis measures the risk level of the system by evaluating the potential consequences and its respective probabilities. In cases which the consequences can ignore or the probability is very low, there is a possibility to make a decision with a single parameter.

Different methods can be used to analyze risks; generally these methods are including qualitative, semi-quantitative, or quantitative. These methods are selected based on the availability of the real data, the required application and the organization decision-making essentialities. Qualitative assessment determines level, consequence and probability of the risk based on significance levels, such as "high", "medium" and "low". The consequence and probability may combine to report the resultant level of risk against the qualitative criteria; while, semi-quantitative methods apply numerical rating scales to report the consequences and probabilities and may combine them to obtain a level of risk using a formula. On the other hand, in quantitative analysis a specific value for consequences and their respective probabilities are calculated and based on that the risk level will be reported in specific units. However, there is not always a possibility to use the quantitative analysis due to lack of information or the relative human factors.

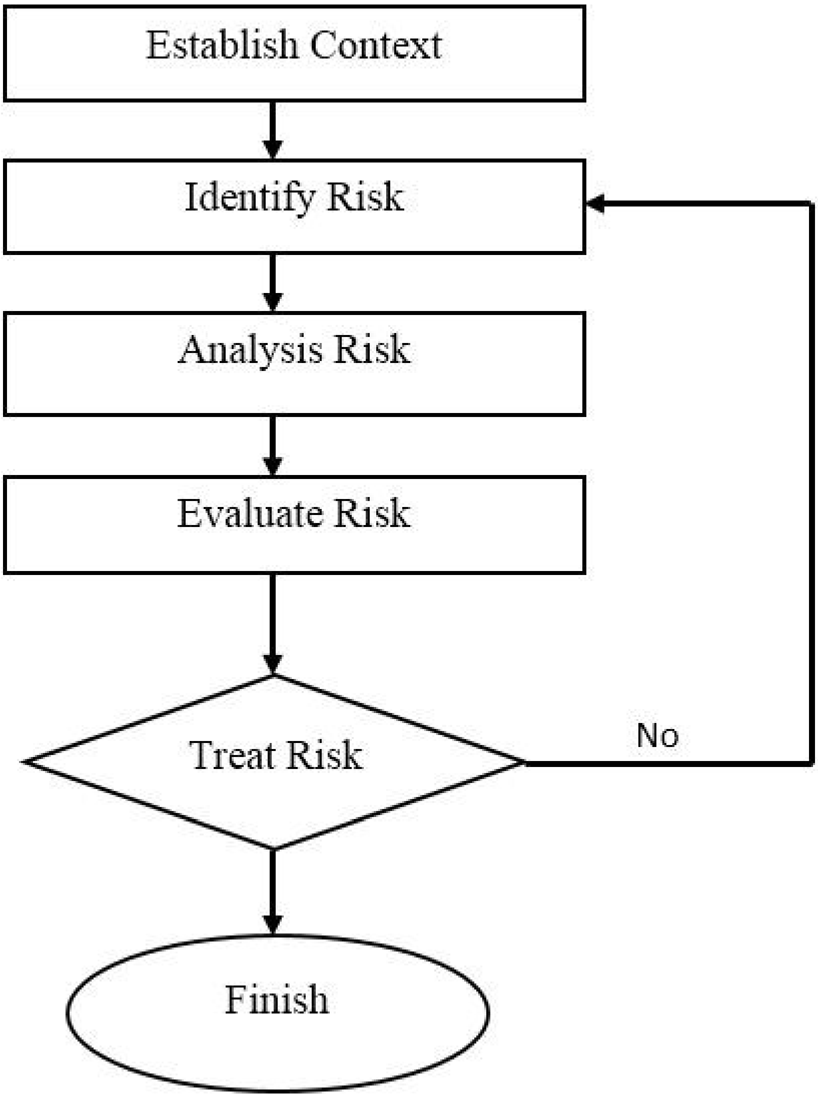

Figure 4.5. Risk Assessment overview

4.4. Simulation

Virtual environments have vital roles in current manufacturing industries, as they facilitate the design of different manufacturing production lines and provide visual analysis tools to create the manufacturing process. Using a virtual environment reduces the risk connected to production changes, production planning time, and cost, while improving the process ergonomic safety [15,16]. There are various software programs available for simulating manufacturing production lines, and one of the most common is Siemens Tecnomatix software. Tecnomatix is developed by the Siemens Company and is practically subdivided into different packages designed to accomplish particular tasks. The package used for analyzing the ergonomic effects on humans is called JACK software; the package used for creating digital models of production lines and examining different possibilities for system layouts is called Plant Simulation; and the package in which the feasibility of the product assembly process is analyzed is called Process Simulate, used for offline programming of robots and the manufacturing process. In order to simulate the process of the brake disc assembly, the Tecnomatix Process Simulate package was used. There are two types of simulation available in Tecnomatix Process Simulate software: time-based simulation and event-based simulation. Usually, time-based simulation includes resources, products, and operations, while for event-based simulation signals should be defined. Time-based simulation is implemented during a specific period of time in which the sequence of operations is predefined. In order to constitute a manufacturing process using the time-based method, it is necessary to define kinematic motions for the non-stationary parts. The main difference between these two types of simulation is that event-based simulations do not have a specific time process, and the sequence of operations is defined according to the process logic box; this means that this simulation uses signal-based logic to determine the operations sequence [17]. In this research, time-based approach and event based approach was applied to model different scenario of human robot collaboration in the manufacturing process. The steps of simulation was described as following lines:

In the first step the CAD models of the assembly components and station should be designed in CATIA or NX software. In the second step the models of robot or gripper should be imported in the Product Design software which is created before in RobCAD or any software has ability to defined links, joints and kinematic parts. During third step the CAD models from first step should be imported in Product Design software. In the fourth steps it’s time to define libraries which is contains library of resources and materials, robots, human during assembly parts to optimize layout. In the fifth step the data should be imported to Process Design to allocate tasks to humans and robots, also define kinematics parts. In the sixth step it’s time to analyze production design parameters. At the following step depend on scenario utilized time based or event based category to perform multi objective optimization of HRC workstation. At the last step apply different scenario of ISO methods to optimize collaboration and reduce risk of collision.

4.5. Experimental tests

In order to apply human-robot collaboration in a real environment it is needed to follow previous steps to test different scenarios. The environment is prepared regarding to risk assessment and risk analysis which identify the dangerous elements of design and provide a safe environment to run applications. Then after, different scenario of human-robot collaboration which are tested before in simulation steps are performed.

4.6. Conclusion

In this chapter, the comprehensive methodology of this thesis has been presented. The main objective of this methodology is to provide safe collaboration between human and robot in the assembly line. Firstly, the potential hazards and risks of the human working beside robots have been described, then the structure of AHP method for having a comparison between human-only system and the one that is based on a human-robot collaboration system has been discussed. In the third step, risk assessment consists of the overall risk analysis process, risk estimation, and risk evaluation has been applied. Risk assessment not only determines risks, their causes, consequences, and their probabilities but also, provides valuable information about the parameters which can affect the main goal. Using risk assessment, tasks associated with hazards based on safety regulations have been identified. In the fourth step, structure of task analysis method for allocating tasks between robot and human has been described and in the next steps of risk assessment including hazard identification, risk estimation and evaluation have been studied during installation with respect to safety standards. Finally a short summary about the virtual environment modeling of the assembly cell has been presented and at last, the sequences of activity should be tested in a laboratory environment.

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Chapter 5

Case study 1: Safety Design and Development of a Human-Robot Collaboration Assembly Process in the Automotive Industry

5.1. Introduction

Today there is strong competition among industries toward factory-wide automation; manufacturers apply automation in their production line since they have a high interest in increasing the production rate without jeopardizing the quality and accuracy of the final product. Recently, robots have played major roles in automated production lines due to their superior capabilities. Although robots have been widely used to perform repetitive, non-critical tasks, such as handling, welding, and joining [1], recently researchers have developed specific studies with the aim of integrating them in a collaborative workspace. A collaborative workspace deals with the cooperation of humans and robots trying to accomplish a specific task. However, using collaborative robots, operator safety should not be put at risk in any aspect; this requires clear task definition and allocation for humans and robots in a collaborative work cell [2].

A safety design framework for human-robot collaboration in the absence of predefined regulations has been proposed by Reference [3]; authors have tried various strategies to design a safe workspace. Their suggested strategies have used different devices, such as safety fences, sources, light curtains, cameras, and robot speed and area restriction stop systems. The effectiveness of the safety design has been evaluated by risk assessment methods; however, still there is a gap between this strategy and safety regulations. A practical case study of human-robot collaboration has been presented in Reference [4]; using inverse kinematic theories, authors have made a control framework to define the robot trajectory completely for the case of the automotive homokinetic joint assembly process.

Authors of References [5,6] have focused on the speed and separation method, defined as one of the available ISO standards for collaborative robots, to increase operator safety in the shared workspace. Having used this standard, the safety of the operator in the manufacturing cell increased by determining the minimum protective distance between humans and robots. With respect to previous contributions in the field, the authors of Reference [7] have investigated the advantage of virtual reality technologies to simulate the assembly and maintenance process in a digital environment that allows the simulation of the human and robot interaction. They proved that these technologies appreciably reduce the time and cost of production development. In Reference [8], in aiming to design novel manufacturing systems, the authors considered the safety issues of the operators with the possibility of planning collision-free paths for multiple robots in a Virtual environment. In Reference [9], the needs of modern manufacturing industries that have led to cooperation between humans and industrial robots were discussed. In this study, the system, called Beware of the Robot (BOR), is used to train the operators in human-robot interaction, considering the safety issues for humans and enhancing production. In Reference [10], the authors explained the design method in hybrid reconfigurable system (H-RS) engineering, which maintains the design method and clarifies the concept. This method was utilized to develop a hybrid reconfigurable work cell for assembling a top-class car chassis. During human-robot collaboration, task allocation is one of the most challenging problems. Researchers of Reference [11] have used the task analysis method to define the necessary order in collaboration tasks in an assembly cell. Using this method, they reduced the chance of duty interference between an operator and the assistant robot.

Authors of [12] have focused on the real human-robot interaction tasks. The three tasks needed for the street-lamp disassembly and bulb replacement, for the disassembly of an electrical appliance and for the assembly of a metallic structure have been accomplished based on their proposed system. A human-robot interaction system has been proposed with specific attention to the two main factors of human tracking system and human-robot distance computation system. The utilization of this innovative approach provides the possibility of achieving the precise location of the operator body and, by using this information, the possibility of determining the minimum distance between human-robot in any conditions. This approach helps to find eventual situations of human-robot collision in the case of small distance between operator and robot. There are only few papers available which apply task analysis in human robot collaboration. [13] Applied task analysis to improve the efficiency of cable assembly operation in cell production system. Using this task analysis method, after determining tasks for human and robot it is possible to arrange the tasks sequences in collaborative order. It was proved that the use of this task analysis method helps to find out the possible problems and the missing tasks to develop the human-robot collaborative algorithm. [14] Have utilized a set of motion, 3D models and vision sensors for real time monitoring and collision detection in human-robot interaction to increase flexibility and safety. This method has shown that, in the case of emergency situation, instantaneous process stop could be replaced by warning the operators, stopping the robot and modifying the robot path. In the present research paper, human-robot collaboration in the case of brake disc assembly process has been evaluated by task analysis method and compared with the manual assembly process to show the performance of the proposed approach.

In this chapter, firstly the effectiveness of human-robot collaboration for the assembly of a brake disc is proven in a general framework by the analytic hierarchy process (AHP) approach and results with respect to different criteria are presented. In the second step, the hierarchical task analysis (HTA) method is used to define and allocate the primary human and robot tasks without their duty interference. In the third step, after human and robot tasks are defined, and the brake disc, as a real case study, assembly process is simulated using the virtual environment software. In the last step, after the efficiency of the model is evaluated by experimental tests in a real workspace situation in laboratory, problems and defects of the human-robot collaboration will be detected and resolved then, new tasks are added to the HTA diagram to improve the efficiency of the human-robot collaboration.

5.2. Automotive Brake Disc

Brake disc is a rotating component of wheel's brake disc assembly applied against brake pads as presented in Figure 5.1. This will delay the shaft rotation, the same what happens in a vehicle axle, to reduce the rotational speed and to keep it stationary. The material is a form of cast iron typically gray iron. The design of brake discs is different, some are simply solid, but some have complex design with fins or vanes joining together. The size of brake disc depends on the weight and power of vehicle. To have better heat transition, noise decreasing, mass reduction and to aid surface-water dispersal in brake disc, holes or slots through the disc have been designed. This design usually is used for motorcycles, bicycles and many cars discs.

To remove dust and gas, discs have been designed by thin channels named slotted discs. This type of discs are used in racing environments to eliminate water and gas and to deglaze brake pads [15, 16]. Another type of the brake disc is floating disc which is splined to prevent thermal stress and cracking. This characteristic will allow the disc to expand in a controlled symmetrical manner and optimize the transfer of undesirable to the hub. [17]

Figure 5.1. Close up of Brake disc

5.3. Manual assembly process of a brake disc

The assembly of a brake disc is completed through a procedure of five sequential steps. (a) In the first step, semi-finished parts, such as the snap ring, upright, and bearing, come from the previous station or from the shelf. (b) In the second step, an operator takes the dust protection plate from the plate box and puts it on the semi-finished parts. Then the operator takes three M6 type screws from the screw box and inserts them into the dust protection plate. (c) In the third step, the operator takes the hub from the hub box and puts it on the dust protection plate, brings the parts to be assembled to the press machine, and puts them in place. At this moment, the press machine inserts the hub inside the previously assembled parts with pressure and then the operator brings back the assembled components to the production cell. (d) In the fourth step, the operator takes the brake disc from the disc box and puts it on the assembled components. (e) In the last step, the operator takes two M8 type screws from the screw kit and inserts them on the assembled parts and tightens them, as shown in Figure 5.2.

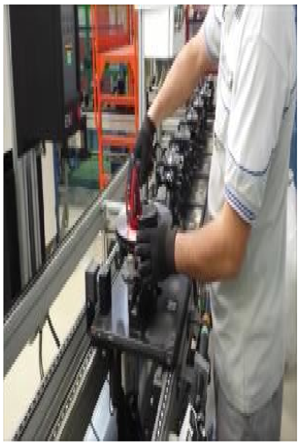
To describe in a more detailed way the working situation of the operator, it is better to clearly define the working conditions, as shown in Figure 5.3. Every day, each operator should work 8 hours/shift, each brake disc weights 5 kg, and the assembly of one brake disc takes around 3 minutes; considering the operator's shift hours and the brake disc assembly period, the operator should assemble approximately 160 brake discs and lift 800 kg throughout each working day.

(a) First step (b) Second step (c) Third step (d) Fourth step (e) Fifth step

Figure 5.2. Brake disc components for assembly operation

(a) First step (b) Second step (c) Third step

(d) Fourth step



(e) Fifth step

Figure 5.3. The sequence steps of the manual brake disc assembly on the production line.

5.4. Quantitative Analysis by the Analytic Hierarchy Process (AHP)

Evaluating the efficiency of a process qualitatively with respect to various criteria for finding the optimum solution is not an easy task; however, using quantitative analysis, such as the analytic hierarchy process (AHP) [18, 19], provides a good solution to satisfy this objective. In the present case study of the assembly of a brake disc, the considered evaluation criteria are productivity, human fatigue, safety, and quality. While the comparative solutions are one that employs a human-only system and one that is based on a human-robot collaboration system, AHP analysis is used as the evaluation methodology. The four criteria of productivity, human fatigue, safety, and quality were considered the most important by both the factory managers and the expert personnel involved in this activity; other criteria were ignored since they would not significantly affect this human-robot collaboration procedure. To implement this activity, three expert personnel participated in decision-making and planning, and they support the author's choice of the AHP method to evaluate the efficiency of the human-robot collaboration.

The AHP analysis proposed by References [20–24] is defined in eight general steps, as follows:

1. Identify the problem and define the goals.

2. Construct the general framework of the AHP analysis in a hierarchically descending order; this means that the objective set at the highest level is followed by the criteria set at the intermediate levels, and then solutions, which are set at the lowest levels.
3. Use the pair-wise comparison scale for AHP preference from References [20–24], ranging from 1–9 (intensity of importance) as shown in Table 5.1. In this scale, 1 expresses the equally-preferred status and 9 expresses the extremely-preferred status.
4. Construct the pair-wise comparison matrix for the four criteria, as in Tables 5.2 and 5.3.
5. Construct the pair-wise comparison matrices of alternatives for each specific criterion; this means that if there are n criteria and m alternatives available in the procedure, there should be n matrices with the size of m × m, as in Tables 5.4 – 5.7.
6. Construct the synthesized comparison matrices of alternatives for each specific criterion to calculate the priority vectors; each value of the synthesized matrix is calculated by dividing the same element in Tables 5.4 – 5.7 by the summation of its column. Each priority vector is then calculated as the average of the new matrix row, as shown in Tables 5.4 – 5.7.
7. Calculate the consistency ratio for the pair-wise matrix of the four criteria to check the consistency of the analysis comparisons.
8. Construct the priority matrix of alternatives (solutions), as in Table 5.8.

The pair-wise comparison matrix of the four criteria, as reported in Tables 2 and 3, aims to show the importance of one criterion over the others [24]. In this research, the intensity and importance of each criteria was chosen through a group decision. This sorted out that (see the columns of Table 5.2) the safety factor has the highest importance intensity, followed by productivity and quality factors, while the human fatigue factor has the lowest importance intensity. The pair-wise comparison of alternatives with respect to each criterion is evaluated at steps 4 and 5 based on the actual system operation. The use of a human-robot collaboration design can give a greater importance to productivity and quality factors so that they have, comparatively, the same intensity and importance to reach the goal in the assembly of the brake disc (Tables 5.4 and 5.5). It can be noted this also reduces the workload burden of the human operator (Table 5.6) while, due to the close range of human and robot cooperation and consequent increase of the injury risk, there might be a much lower safety level in the human-robot design (Table 5.7) [11].

Consistency of the analysis comparison is determined by calculating the consistency ratio as in Equation (1):

$$CR = \frac{CI}{RI} \tag{1}$$

where *CI* is consistency index and *RI* is average random consistency.

RI is a predefined value depending on the size of the pair-wise comparison matrices; in this case, due to the size of the pair-wise comparison matrix for the four criteria, which is 4 × 4, *RI* is equal to 0.9 [22]. *CI* is calculated according to Equation (2):

$$CI = \frac{\lambda_{\max} - n}{n - 1} \tag{2}$$

where $\lambda_{\max}$ is the maximum eigenvalue and n is the size of the four criteria pair-wise comparison matrix. To calculate $\lambda_{\max}$, the weighted sum matrix of Table 8 is calculated by multiplying each priority vector element into the respective column and adding the values. Then, each element of the weighted sum matrix is divided by the respective priority vector element and the average values are reported as $\lambda_{\max}$. A consistency ratio lower than 0.1 proves the suitability of the pair-wise comparison matrix. More information related to the estimation of the consistency ratio is reported in Reference [20].

Table 5.1. Average random consistency (RI)

Size of matrix	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
Random consistency	0	0	0.58	0.9	1.12	1.24	1.32	1.45	1.49

The last step is to construct the priority matrix of alternatives and to calculate the overall priority vectors. The overall priority vector of each solution is calculated as summation of the priority vector of each alternative multiplication (in this case there are four priority vectors, related to the four criteria of safety, productivity, quality, and human fatigue for each alternative) to the respective priority vectors listed in Table 8. The alternative with the highest overall priority value provides the result of the analysis. Following the AHP procedure described above, the hierarchy of the problem is developed as shown in Figure 5.4.

The priority of each decision alternative with respect to its contribution to different criteria is decided by project managers and is presented in Table 5.2. By determining the pair-wise comparison matrix for each criteria, it is possible to complete the calculation using manual estimation or expert choice as an AHP in the developer software.

Table 5.2. Pair-wise comparison matrix for four criteria

Human-Robot Collaboration	Productivity	Quality	Human Fatigue	Safety
Productivity	1	1	2	1/2
Quality	1	1	2	1/2
Human Fatigue	1/2	1/2	1	1/6
Safety	2	2	6	1

After developing Table 5.2, the pair-wise comparison matrix is synthesized by dividing the matrix of each element by its column total. For instance, the value 0.222 in Table 5.3 is calculated by dividing 1 (from Table 5.2) by 4.5, which is the sum of all the column terms shown in Table 5.2 (1 + 1+ 1/2 + 2).

The priority vector of the synthesized matrix is calculated by dividing the row averages, as shown in Table 5.3. For instance, the productivity priority based on human-robot collaboration criterion, as shown in Table 5.3, is estimated by dividing the sum of the rows (0.222, 0.222, 0.1818, and 0.230) by the number of columns (4).

The priority vector for human-robot collaboration, shown in Table 5.3, is given below:

$$\begin{bmatrix} 0.214 \\ 0.214 \\ 0.097 \\ 0.476 \end{bmatrix} \tag{3}$$

Table 5.3. Synthesized matrix for human-robot collaboration

Human-Robot Collaboration	Productivity	Quality	Human Fatigue	Safety	Priorities
Productivity	0.222	0.222	0.1818	0.230	0.214
Quality	0.222	0.222	0.1818	0.230	0.214
Human Fatigue	0.111	0.111	0.9090	0.0768	0.097
Safety	0.444	0.444	0.5454	0.460	0.476

$\lambda_{max} = 4.0197$, $CI = 0.00656$, $RI = 0.9$, $CR = 0.00729 < 0.1$

$$0.214\begin{bmatrix}1\\1\\1/2\\2\end{bmatrix}+0.214\begin{bmatrix}1\\1\\1/2\\2\end{bmatrix}+0.097\begin{bmatrix}2\\2\\1\\6\end{bmatrix}+0.476\begin{bmatrix}1/2\\1/2\\1/6\\1\end{bmatrix}=\begin{bmatrix}0.860\\0.860\\0.390\\1.914\end{bmatrix} \quad (4)$$

By dividing all the weighted sum matrix elements, obtained from Equation (4), by their respective priority vector elements as below:

$$0.860/\ 0.214 = 4.0186 \quad (5)$$

$$0.860/0.214 = 4.0186 \quad (6)$$

$$0.390/0.097 = 4.0206 \quad (7)$$

$$1.914/0.476 = 4.0210 \quad (8)$$

The $\lambda_{\max}$ can be calculated as the average of the above values:

$$\lambda_{max} = (4.0186 + 4.0186 + 4.0206 + 4.0210) \div 4 = 16.0788/4 = 4.0197 \quad (9)$$

It is now possible to calculate the consistency index, *CI*:

$$CI = \lambda_{max} - n/n - 1 = 4.0197 - 4/4 - 1 = 0.00656 \quad (10)$$

Based on References [14–19], as presented in Table 1, for a matrix with the size of 4, the random consistency ratio, *RI*, is 0.9 and the consistency ratio, CR, is calculated as follows:

$$CR = C\,I/R\,I = 0.00656/0.9 = 0.00729 \quad (11)$$

Due to the fact that *CR* is less than 0.1, the judgments are acceptable. Similarly, all the pair-wise comparison matrices along with the priority vectors for different criteria are calculated, as presented in Tables 5.4–5.7.

Table 5.4. Pair-wise comparison matrix for productivity

Productivity	**Human**	**Human-Robot**	**Priority Vector**
Human	1	1/7	0.25/2 = 0.125
Human-Robot	7	1	1.75/2 = 0.875

Table 5.5. Pair-wise comparison matrix for quality

Quality	Human	Human-Robot	Priority Vector
Human	1	1/7	0.25/2 = 0.125
Human-Robot	7	1	1.75/2 = 0.875

Table 5.6. Pair-wise comparison matrix for human fatigue

Human Fatigue	Human	Human-Robot	Priority Vector
Human	1	1/6	0.285/2 = 0.1425
Human-Robot	6	1	1.714/2 = 0.857

Table 5.7. Pair-wise comparison matrix for safety

Human Fatigue	Human	Human-Robot	Priority Vector
Human	1	1/6	0.285/2 = 0.1425
Human-Robot	6	1	1.714/2 = 0.857

Table 5.8. Priority matrix of alternatives

Overall Priority Vector	Productivity	Quality	Human Fatigue	Safety
Human	0.02675	0.02675	0.0138	0.3965
Human-Robot	0.1872	0.1872	0.0831	0.0790

The overall priorities of the human system and the human-robot system can be evaluated according to:

Overall priority of the human system = 0.02675 + 0.02675 + 0.01380 + 0.39650 = 0.4638

Overall priority of the human-robot system = 0.1872 + 0.1872 + 0.0831 + 0.0790= 0.5365

Their values are 0.4638 and 0.5365, and this confirms that the human-robot system is the preferred solution which can satisfy the criteria.

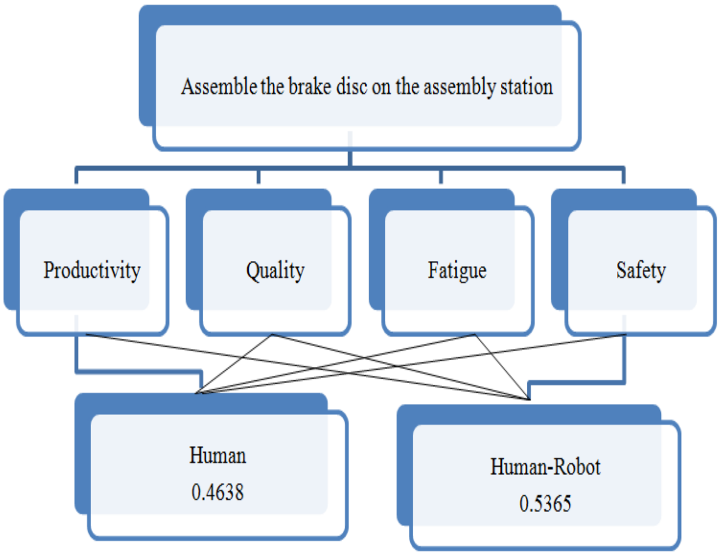


Figure 5.4. The analytic hierarchy process (AHP) model of tasks

5.5. Workspace Components

The assembly of a brake disc is performed in several steps in an actual production environment. In the laboratory environment, it is supposed that the human-robot collaboration can be concentrated into one cell. This experimental cell is composed of two different zones: picking and assembly areas. The picking area is the zone where the components to be used in the assembly process are located; the robot should be able access to them. In the assembly area, the semi-finished parts are located and the assembly process has to be performed by the operator and robot. The components are located on the workbench, including the screw kit, brake disc, dust protection plate, tip kit, and semi-finished parts; the robot manipulator picks them in an ordered sequence as shown in Figure 5.5.

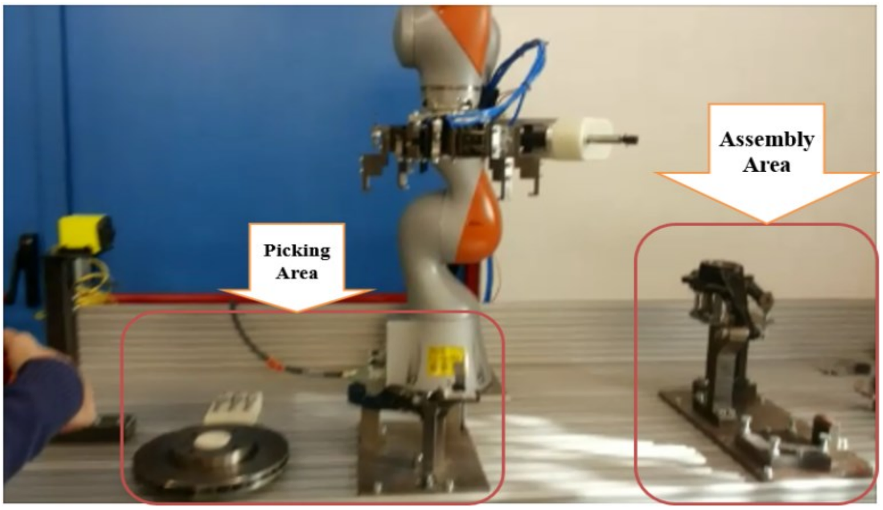


Figure 5.5. Workbench area

In order to investigate the feasibility of this activity, a robot manipulator with seven degrees of freedom has was introduced to support and help the operator to complete the assembly activity. The main purpose of applying a robot in the assembly process is to improve operator ergonomics and increase productivity. As mentioned before, tasks are generally subdivided into three main categories: picking, placing of assembly parts, and tightening of screws. These tasks will be allocated to the operator or to the robot based on the sensitivity of tasks and the ability of humans and robots to perform those tasks. To accomplish these arrangements, sequences and proper tasks allocation are quite critical and require a complicated process. If the assignment of tasks does not take place properly, then the operator will probably face serious ergonomic problems, such as muscular and back pain, due to performing repetitive tasks and heavy workloads. Due to these facts, the robot manipulator was introduced to reduce the workload and improve the ergonomics of the operator. The location of the robot manipulator during this collaborative activity is very important with respect to the operating tasks and feasibility of the assembly.

5.5.1. Framework of applying Safety-sated Monitored Stop (SMS) in collaborative workspace

In order to respect safety regulations, and based on ISO 10218-2 norm 5.10.2 [25], an emergency stop button is located at end of the workbench which is connected to the robot with cables and controlled by software to stop the robot motions. In this activity, the safety-rated monitored stop (SMS) was used to fulfill the safety regulations. The robot has no motion whenever the operator is inside the collaboration space. Whenever the operator wants to enter the collaboration area, he should press the button to command the robot to stop its movements until he performs his tasks. After the operator finishes his duties, he should again press the button, which means he wants to exit the collaborative zone. Moreover, after the operator completely exits, the robot manipulator can continue its jobs and complete the tasks.

In order to achieve effective collaboration between humans and robots, it is necessary to plan suitable arrangements and define clear duties considering capability and reliability, both for the human and the robot. In the advanced reproduced experimental tests in laboratory environments, proper sensors, such as safety mats, laser scanners, or other detective devices, can be used. These detective devices are able to recognize and detect any objects in the surrounding environment and, by proper elaboration of this kind of information, prevent possible collisions. The mentioned solution based on a stop button at the end of the workbench was implemented in a preliminary practical test based on the manual assembly operation. The collaboration activity was repeated five times and took two working weeks to accomplish.

5.6. Task Analysis

5.6.1. Human-robot collaboration interaction levels

Collaboration of human in vicinity of the robot increases probability of the human body injury and pain. It is important to know the tolerance of human body's injury to simulate and design of collaborative environment during human -robot collaboration. Many simulations and experiments have been completed to examine these limitations [26-28]. Theses parameters were defined based on the robot speed, human distance from the robot, acceleration, and a size of contact area which have considerable influences on the injury tolerance magnitude. Numerous categories of body pain and injury are available in the tolerance index. Many researches have been done about tolerance limits of whole body structure when static and dynamic simulations are applied.

During applying stimuli to the human body, the human pain tolerance limits are obtained from the human response. Some parts of human body such as hand, arm, back and head are under most frequent exposure to the hazard which critical forces were found for them respectively as 140N, 180N, 240N and 130N [29]. The most remarkable critical part of human body is head part.

The human head is considered as a complex system and consists of the three main components. These components are the skull with cranial and facial bones, the skin and other soft tissue covering the skull, and the brain. Head injuries are categorized as superficial or deep, and include contusion, laceration and abrasion.

During the skull fracture, one or more skull bones break due to the injury. The skull fracturing happens due to the impaction of the internal part of the skull by the brain or the internal pressure in the brain. According to [30], the threshold of the brain injury is determined based on Aran's low that describes the fracture of middle ear as a reason for this type of injury. These types of injuries can be considered as unconstrained impact and constrained impact injuries as shown at Figure 5.6. [31].

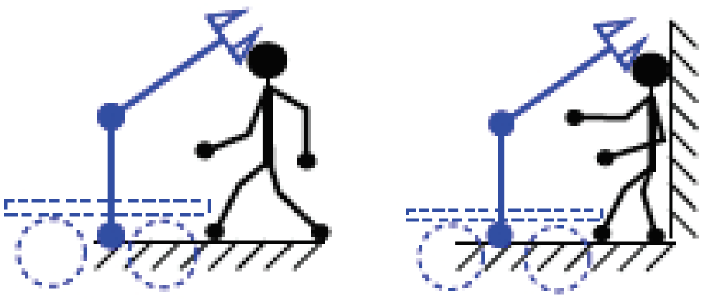


Figure 5.6. (a) Unconstrained impact, (b) Constrained impact

Serious injuries may be resulted from the second impact type, since a head is exposed to maximum impact force without the chance for human to run out of the risky zone.

Measuring injuries criteria of the skull bone fracture, brain disorder thresholds and pain tolerance can be achieved from the human-robot interaction analysis. Based on [31] the fracture threshold of different parts of skull is different; the fracture threshold of different parts of skull is presented at Table 5.9. and Figure 5.7.

Table 5.9. Skull bone fracture forces [31]

Bone N ame	Fracture Force, KN
Maxilla	0.66
Mandible	1.78
Parietal	3.12
Frontal	4
occipital	6.41

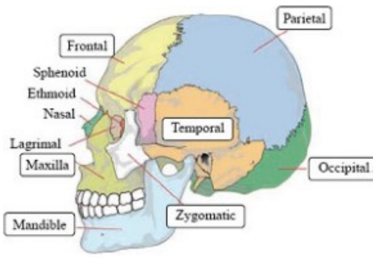


Figure 5.7. Different parts of skull

The impact force and collision distance are the most important points of injury severity in mechanical contact and collision accident. Robots physical characteristics, actual configurations, approaching speed, direction, and the contact duration constitute the impact force. According to [27, 32-33], some other parameters such as task specifications, rate of the robot failure, safety features presence and reliability, the instrument shape and control methods can influence this measurement.

According to the National Highway Traffic Safety Administration (NHTSA) [34], the maximum allowable value of HIC is 700 representing 25% of serious injury with maximum head acceleration of 70g (3,5KN) during the impact period of 15ms. Based on Canadian Motor Vehicle Safety Regulations Standard (CMVSS) [35], this value was reported as 80g which is related to the fracture of the frontal bone.

To consider HIC value it is necessary to know the robot operating and structural characteristics such as speed, load, braking and idle time. However, it is important to mention that, personnel approaching speed and the reaction time might contribute to this measurement. The maximum authorized head acceleration is limited to 62g (3.12 KN) for interaction levels of L3 and L4.

5.6.2. Task decomposition based on HTA

There are various methods available for analysis of the operation tasks. These methodologies include the hierarchal task analysis (HTA), goal-directed task analysis, and cognitive tasks that are used to model human-robot interactions [36]. The HTA method is a scientific method used for determining human tasks, regarding different ergonomics and human factors [37]. HTA has numerous applications in different areas, such as entertainment, police and military, space exploration, manufacturing, and mining and agriculture [38]. In order to constitute the HTA diagram, all tasks should be defined as goals and sub-goals; they all must be completed to achieve the final goal [39]. In this specific study of human-robot collaboration, HTA [40-42] would be a very effective method to determine the collaborative tasks between humans and robots. The same scenario applied for AHP is used for the HTA method. To complete this activity, the same three expert personnel participated in the planning and defining of tasks; one person was responsible for managing and consulting, with more than five years of experience, and the two others were responsible for programming and running the application. The two persons trained in programming and safety regulations of robots, responsible for performing the collaborative activity, worked with the robotic prototype in the laboratory environment; one was responsible for direct collaboration and assistance with the robot and one took care of monitoring tasks and turning off the robot in the case of emergency. The robot programmer was trained for a year in the java programming exclusively used for the KUKA robot; the other expert is a PhD researcher who has studied the challenges and difficulties of human-robot collaborative procedures for more than three years. The overall methods flowchart for defining the human-robot collaboration task is presented in Figure 5.8. As is clear from Figure 6, the first step is data acquisition by direct observation in a real production environment. After recording all necessary information, the operation sequences are categorized based on the related skills and capabilities to clear the framework objective. Once the operation sequences are identified, the general process should be decomposed into separated unified tasks according to the hierarchal task analysis (HTA) method [40-41].

This methodology helps to distinguish between operator and robot roles [11] in the assembly process, as shown in Figures 5.9 and 5.10. Based on Figures 5.9 and 5.10, different roles were defined for the human and the robot; however, the main tasks for the operator include inserting screws and hubs, while the robot is tasked with performing the assembly process and tightening the screws. In the fourth step, HTA is applied to combine the operator and robot tasks in a collaborative order, which constitutes the new task table. Finally, the suggested hybrid task algorithm should be evaluated to verify the feasibility of the proposed methodology. Using the HTA method, tasks are defined as sub-goals, as shown in Table 5.10, with the related task's process time period. In order to constitute the HTA algorithm of the brake disc assembly, the main goal of the system is considered as equal to the main robot manipulator's goal; in this way, the assembly of the brake disc is recorded as the super-ordinate goal 0 in the HTA algorithm, as shown in Table 5.10. To achieve the main goal, sub-goals should be completed. Sub-goals are subdivided into three groups: sub-goal 1 (assembles the dust protection plate); sub-goal 2 (positions the hub on the plate and change the tip for screwing); and sub-goal 3 (completing the assembly of brake disc). Sub-goals are subsequently divided into minor goals, as shown in Table 5.10. It is important to mention that when there is a need for more details, it is necessary to add lower-level goals to the model.

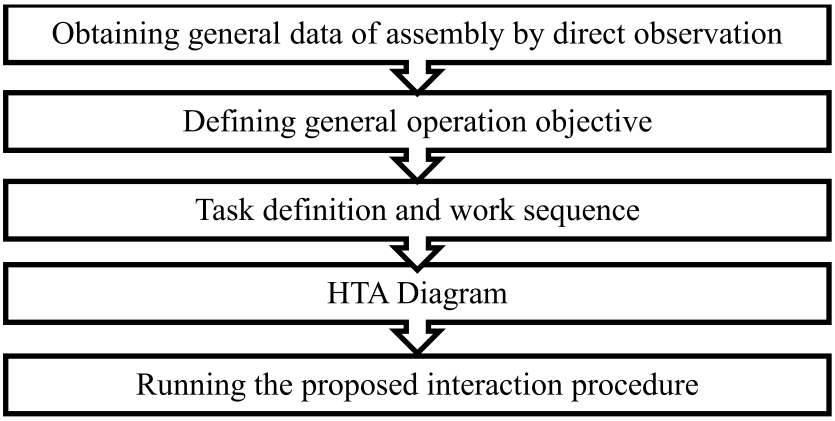


Figure 5.8. Sequence of the task development

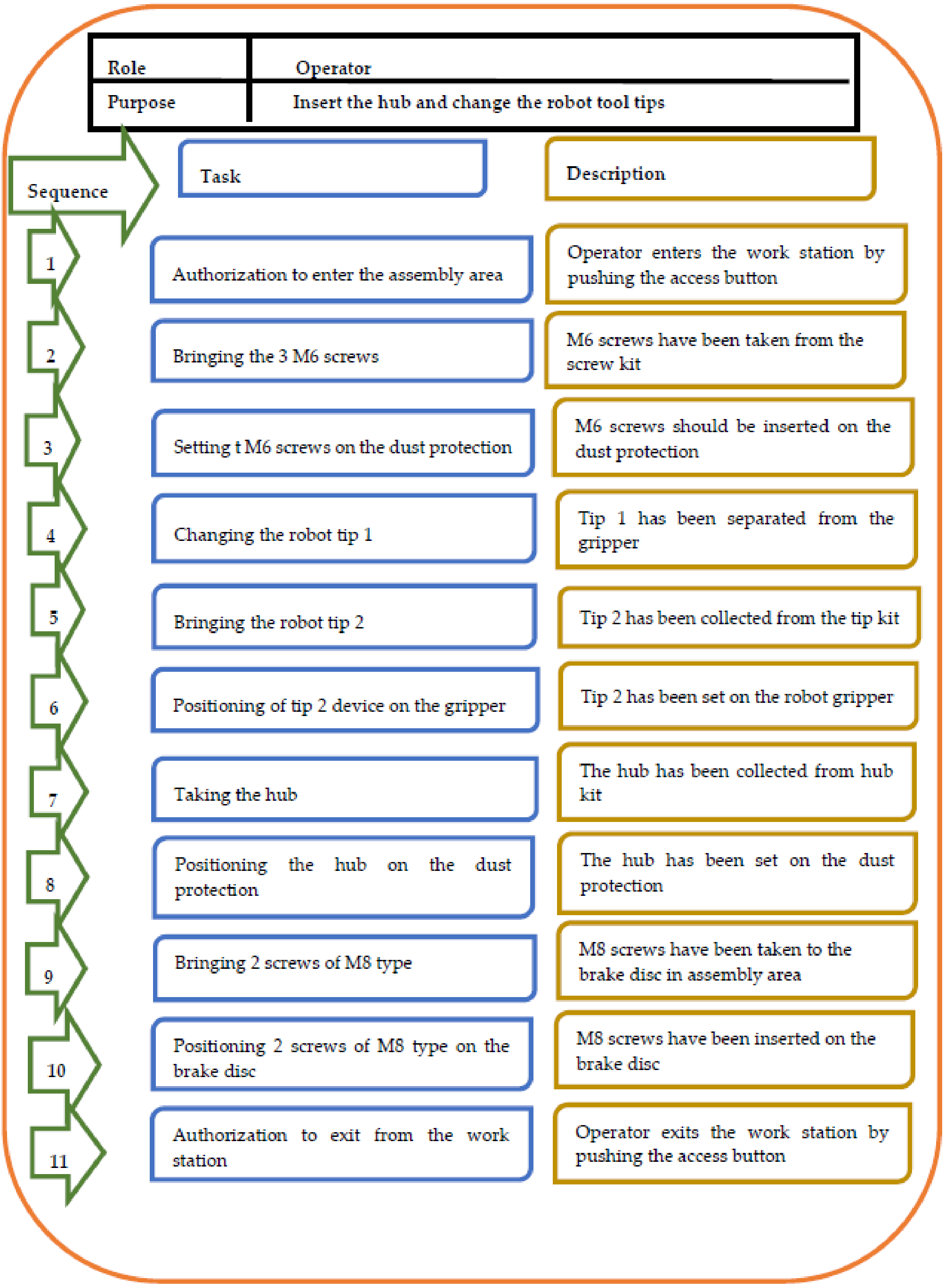


Figure 5.9. Operator’s tasks allocation and sequences

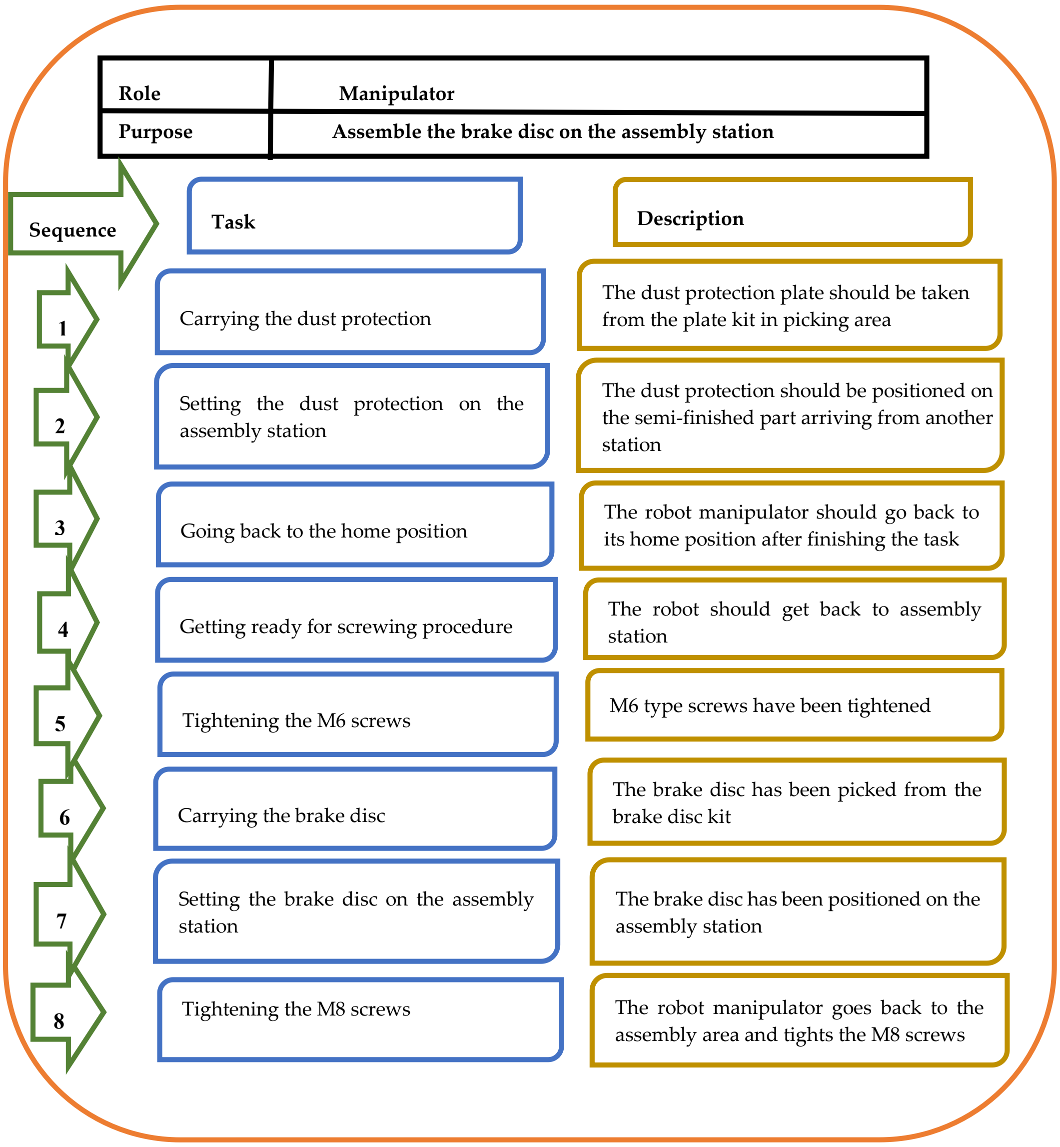


Figure 5.10. Robot’s tasks allocation and sequences

Table 5.10. Hierarchical task analysis (HTA) table of the brake disc assembly operation.

Super-ordinate	Task Components, Operations, and Plans	Timelines	Notes
0	Assembly of the brake disc on the assembly station; Plan 0. Do 1, 2, and 3, then exit.	-	This is a collaborative job between human and robot to assemble the brake disc assembly on the assembly station.
	1. Assemble the dust protection plate on the assembly station	1. 0–91 s	
	2. Insert hub and change the robot tool tips	2.92–122 s	
	3. Assemble the brake disc on the assembly station	3.123–203 s	
1	Assemble the dust protection plate on the assembly station; Plan 1. Do 1.1, 1.2, 1.3, then 1.4, and 1.5 three times, then 1.6, 1.7, and 1.8 three times, then 1.9, and exit.	-	The robot takes the dust protection plate from the picking area, then positions it on the assembly station; the operator pushes the button to enter the work area, then takes three M6 screws from the screw kit and positions them on the dust protector. The operator asks to exit from the work station and releases the button to authorize the robot to continue the assembly job. The robot goes to the proper position on the assembly area for screwing, and after having finished screwing, the robot returns to the home position.
	1.1. Take the dust protection plate	1.1. 0–13 s	
	1.2. Position the dust protection on the assembly station	1.2. 14–30 s	
	1.3. Ask to enter the work station	1.3. 31–35 s	
	1.4. Take three M6 type screws from the screw kit	1.4. 36–38 s	
	1.5. Position the M6 screws on the dust protection	1.5. 39–47 s	
	1.6. Ask to exit from the work station	1.6. 48–50 s	
	1.7. Prepare for screwing	1.7. 51–54 s	
	1.8. Tighten the M6 screws	1.8. 55–86 s	
	1.9. Go back to the Home Position	1.9. 87–91 s	

2	Insert the hub and change the robot tool tips; Plan 2. Do 2.1, 2.2, 2.3, 2.4, 2.5, 2.6, 2.7, then exit.	-	The operator asks to enter the work area, and pushes the button to alarm the robot. The operator takes out the tip 1 from the gripper and puts it in the tip kit, then takes the tip 2 and positions it on the gripper. The operator positions the hub on the dust protection plate. Then, the operator exits the area and releases the button.
	2.1. Ask to enter the work station	2.1. 92–95 s	
	2.2. Change the tip 1	2.2. 96–98 s	
	2.3. Take the tip 2	2.3. 99–101 s	
	2.4. Position the tip 2 on the gripper	2.4. 102–108 s	
	2.5. Take the hub	2.5. 109–110 s	
	2.6. Position the hub on the dust protection plate	2.6. 111–119 s	
	2.7. Ask to exit from the work station	2.7. 120–122 s	
3	Assemble the brake disc on the assembly station; Plan 3. Do 3.1, 3.2, 3.3, then do 3.4,3.5 two times, then 3.6 two times, then 3.7, 3.8 two times, then 3.9, and exit.	-	The robot goes to the brake disc kit and takes one disc, then positions it on the hub in the assembly station. The operator pushes the button to enter the work area. The operator takes two M8 screws from the screw kit and positions them on the brake disc in the assembly area, then goes out and releases the button. The robot goes to the assembly area and does the screwing, then the robot returns to the home position.
	3.1. Take the brake disc	3.1. 123–142 s	
	3.1. Position the brake disc on the assembly station	3.2. 143–150 s	
	3.2. Ask to enter the work station	3.3. 151–153 s	
	3.3. Take two M8 type screws	3.4. 154–167 s	
	3.4. Position the two M8 screws on the brake disc	3.5. 168–171 s	
	3.5. Ask to exit from the work station	3.6. 172–174 s	
	3.6. Prepare for screwing	3.7. 175–181 s	

	3.7. Tighten the M8 screws	3.8. 182–198 s	
	3.8. Go back to the Home Position	3.9. 199–203 s	

5.7. Robot specifications

In chapter 2 the details of Robot KUKA LBR IIWA was described. This kind of robot was used during simulation and experimental tests in order to apply different Human Robot Collaboration scenarios.

5.8. Simulation procedure

Rapid prototyping requires applying of process planning's tools and methods. Virtual environments have vital roles in current manufacturing industries, as they facilitate the design of different manufacturing production lines and provide visual analysis tools to create the manufacturing process. Using a virtual environment reduces the risk connected to production changes, production planning time, and cost, while improving the process ergonomic safety [43,44]. Robotic virtual simulation helps designers to find optimal solutions to evaluate different scenarios during the process planning. Work cell simulation not only provides the opportunity for fast defect detection and the process improvement, but also reduces the chances of operator's injury during the risky situations. There are various software programs available for simulating manufacturing production lines, and one of the most common is Siemens Tecnomatix software. Tecnomatix is practically subdivided into different packages designed to accomplish particular tasks. The package used for analyzing the ergonomic effects on humans is called JACK software; the package used for creating digital models of production lines and examining different possibilities for system layouts is called Plant Simulation; and the package in which the feasibility of the product assembly process is analyzed is called Process Simulate, used for offline programming of robots and the manufacturing process.

5.8.1. Sequence-based Vs. Event-based simulation in Process Simulate

There are two types of simulation available in Tecnomatix Process Simulate software: sequence-based simulation and event-based simulation. Usually, sequence-based simulation includes resources, products, and operations, while for event-based simulation signals should be defined. Sequence-based simulation is implemented during a specific period of time in which the sequence of operations is predefined.

The main difference between these two types of simulation is that event-based simulations do not have a specific time process, and the sequence of operations is defined according to the process logics; this means that this simulation uses signal-based logic to determine the operations sequence [45]. A sample of a simulation in Tecnomatix Process Simulate is shown in Figure 5.11.

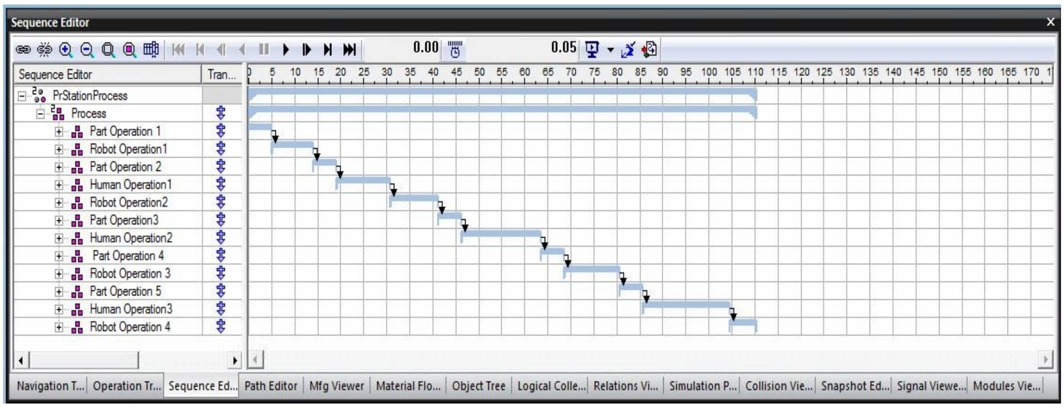


Figure 5.11. Schematic of operations modeling in Process Simulate

Generally advantages and disadvantages of a sequence-based model are as following:

- ✓ Quick modeling of the process in a desired path
- ✓ Possibility of easy and less time-taking modify of the task sequences
- ✓ Obtaining simplified model of a complex procedure
- ✓ Capable of modeling the operator (dummy) to monitor the ergonomics issues
- Cannot be applied for complex procedures

- Needs extra modification to apply in real case scenarios and advantages and disadvantages of the event-based model are:

- ✓ Can handle modeling of complex procedures
- ✓ Different scenarios can be tested during simulations
- ✓ Cab be applied in real industrial procedures
- Time-taking and difficult modeling
- Unadaptable scenarios would be generated

5.8.2. CAD parts preparation for simulation in Process Simulate

All the parts are prepared in NX and CATIA V5.20; however, if any part is designed out of the NX software it is necessary to transfer all the file formats to the JT (Jupiter Tesselation) format in NX. The parts imported to the NX software are divided into two categories; the first category is related to the static links, for which no movements are defined in the virtual environment. In other words, they are stationary parts of the assembly line, such as fixtures, bases, rails, desk, upright, bearing, screws, and snap rings, as shown in Figure 5.12. On the other hand, the parts in which movement is considered are called dynamic links, such as platforms, grippers, robots, etc. In order to input all the designed parts into the Process Simulate software to build the assembly line, the only readable format for the files are in the COJT format; thus, the file formats are converted in Process Simulate software once again to the COJT format.

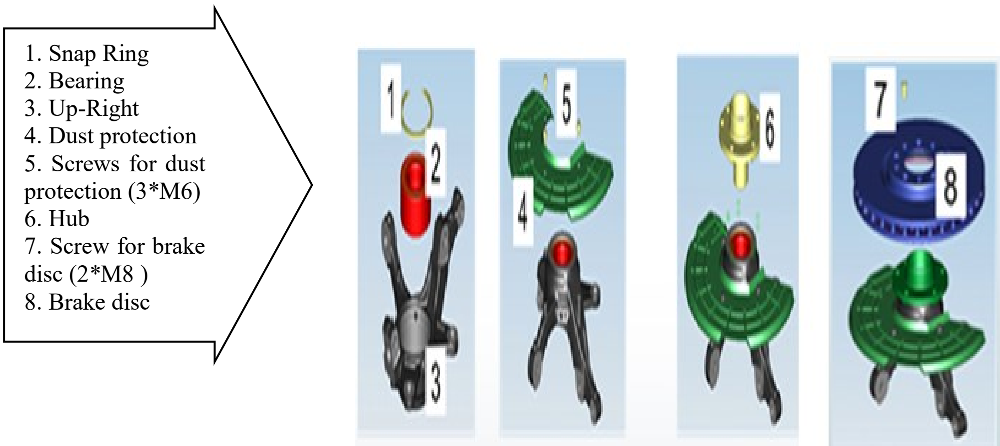
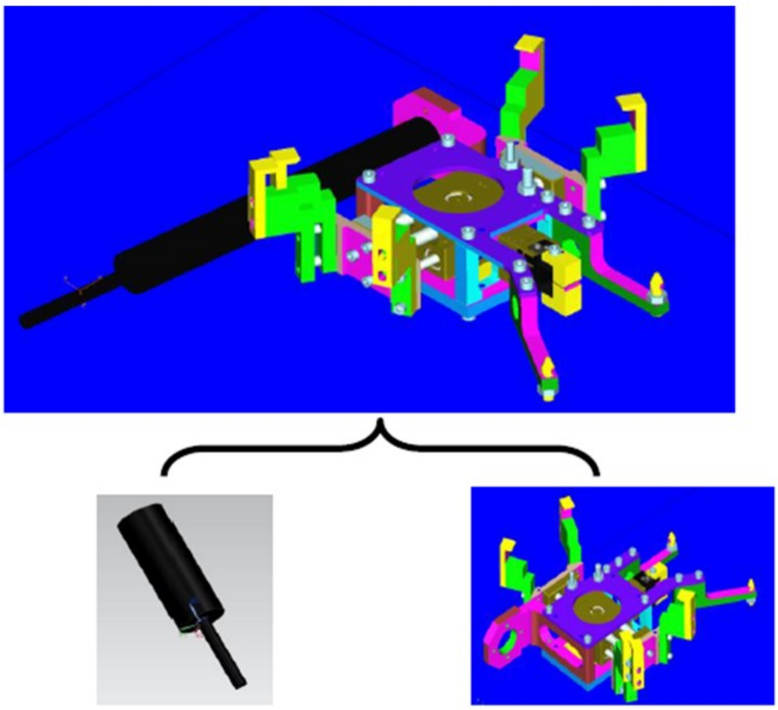


Figure 5.12. CAD parts in NX software

5.8.3. Gripper model

Generally, robots consist of arms and an end effector; the gripper is one of the most common type of end effectors mounted on the end of the robot arm. The primary role of the gripper is for the picking and placing of various objects during the process; however, it is possible that the gripper has multifunctional tasks, as in this research, in which the tasks include picking, placing, and screwing.

Based on the operational tasks of the gripper, it has to be designed in three parts: the base part, the screwing part, and the fingers. As mentioned before, all the parts should be prepared in the format required by the NX software and then imported into Process Simulate, including the gripper parts. In order to introduce a part as gripper to perform the picking and placing operations, it is necessary to define the tool center point and its exact location where it is attached to the robot (tool base frame). The tool center point is located at the center of the gripper facilitating the movement of the gripper' arm. The schematic of the gripper is shown at Figure 5.13; Process Simulate just monitors the collision for the gripper' arm.



a) Screwing part b) Fingers

Figure 5.13. CAD model of the gripper. a) Screwing part- b) Fingers

5.8.4. Defining kinematic characteristics of the gripper

After the gripper is imported into Process Simulate, the kinematic characteristics are used for defining the dynamic link and motion of the gripper. In order to simplify the kinematic representation of the gripper in Process Simulate [29], static and dynamic links should be defined. The model of the gripper components is subdivided into seven parts, including one link that belongs to the base part which has static link characteristics, five links that belong to the finger part and have dynamic link characteristics, and one link that belongs to the screw part and has dynamic link characteristics. The relationship between the links determines the sequence of kinematic chain. The main link or in other words the parent link control sub-links movement. Without defining the appropriate kinematic characteristics, there is no possibility of using parts for a specific application such as gripper. The kinematic chain is define in Process Simulate using the kinematic editor option. The kinematic chain of the gripper is shown in Figure 5.14.

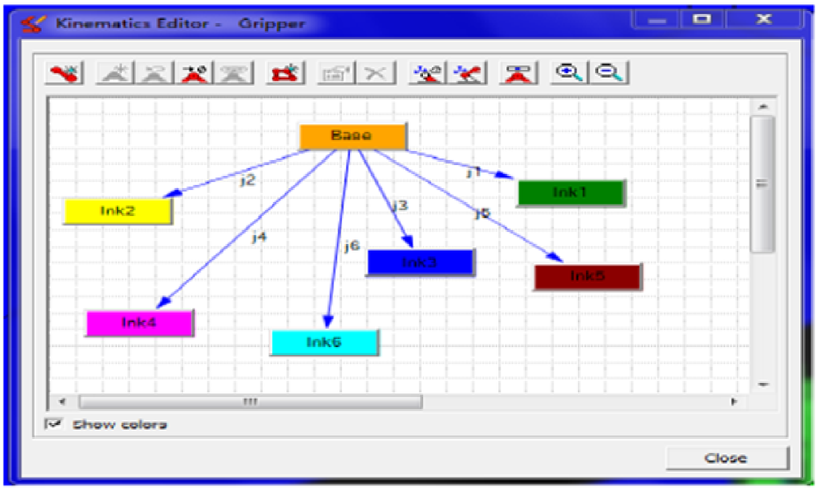


Figure 5.14. Kinematic links of the gripper

5.8.5. Placing robot in the appropriate position

The manufacturing cell resources' location should be defined in the first step; these stationary parts including table and fixtures should be located before starting to define the robot location to maximize the flexibility of the robot for performing the tasks. Resources should be positioned near to the robot's center point.

Determining suitable position to place the robot in the workspace is a challenging issue; Process Simulate provides the ability to find the optimum location for the robot at the work cell. Using 'Robot Smart Place' tool is leaded to test the robot performance in different locations with respect to the position of other components; however since the tool center point is not updated through the robot location changing it requires to update the tool center point position manually. Radius of the robot movement is shown at Figure 5.15.

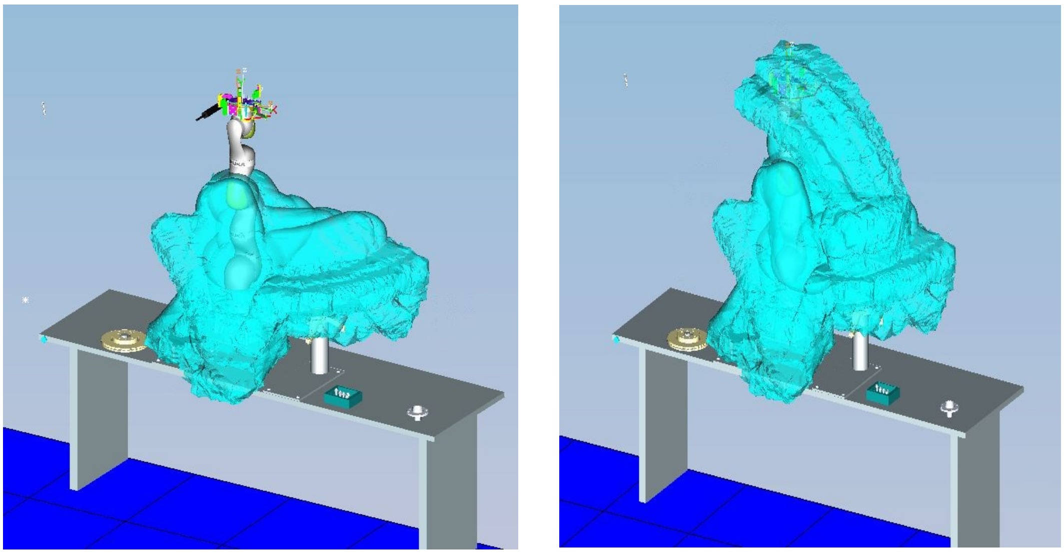


Figure 5.15. Radius of the robot motion

5.8.6. Human modeling in Process Simulate

Human models can be modeled in Process Simulate with different weight and length as shown at Figure 5.16. The weight and length of the human model are considered as 85 kg and 185 cm respectively.

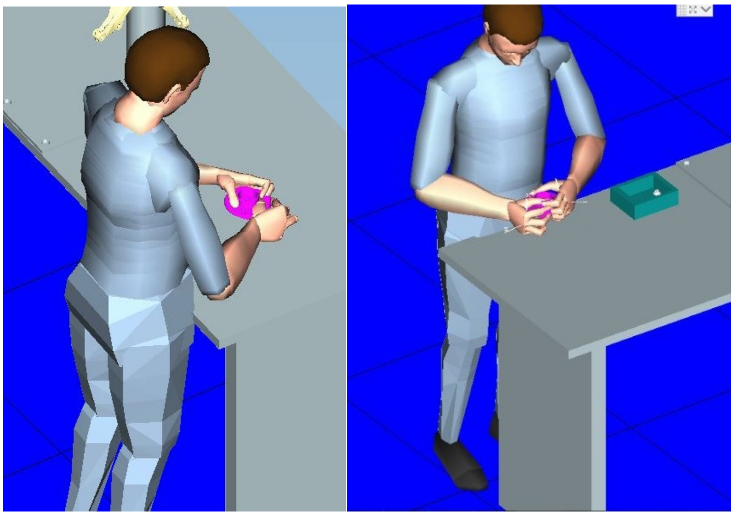


Figure 5.16. Human model in process simulate

5.8.7. Robot Joint sensors definition

In order to define the robot joint sensors, the option ‘Joint Value Sensors’ has been used in Process Simulate package. These sensors will control the robot motion during its operations. To create the joint value sensors for the robot, it is necessary to first define the robot positions during the process using the ‘Pose Editor’ option as shown in Figure 5.17. Under the ‘Poses’ in Pose Editor icon the possible locations of the robot during performing of the tasks are defined.

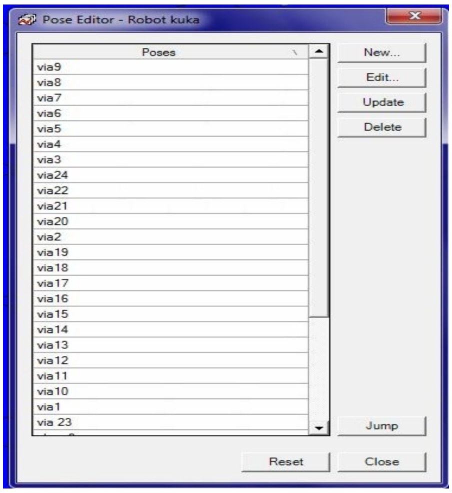


Figure 5.17. Pose definition

After completing the Pose Editor table, different types of the robot joint sensor can be defined using the Cyclic Event Evaluator (CEE) option as shown at Figure 5.18.

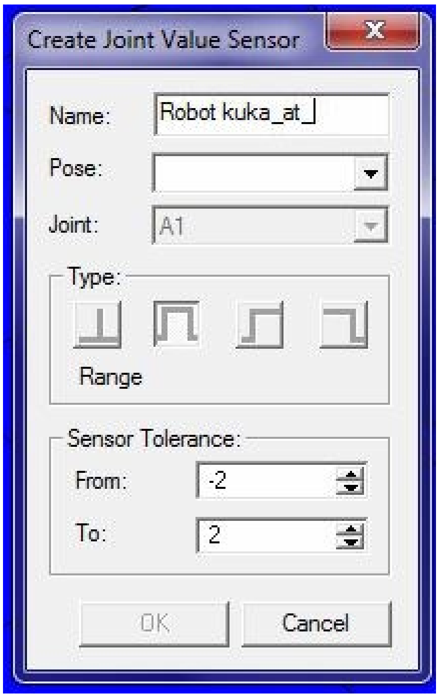


Figure 5.18. Defining Joints' sensor

5.8.8. Modeling proximity sensors

In order to detect all parts and operator during the assembly process, Proximity Sensors can be used; these sensor should be firstly designed as separate CAD models and then the location of them should be determined. Having defined the position of the proximity sensors, they should be assigned to the respective part and the detection range of sensors should be determined as shown at Figure 5.19. These sensors can be defined by using the option CEE in Process Simulate.

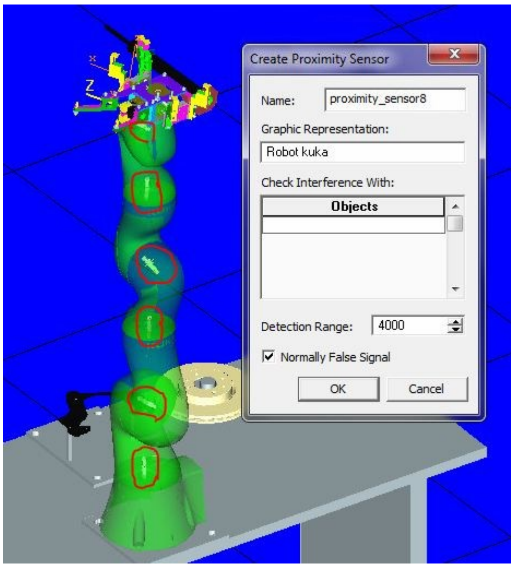


Figure 5.19 Defining proximity sensor

5.8.9. Signal generation

In order to add logic to the modeling, signals should be generated for the all devices and robots. Signals may be an input or output signals which control the initiation of the operation during the modeling.

Signal generation can be performed for robots using 'Signal Generation' option under the command CEE. Using 'Create Robot Start Signals' under signal generation option, the robot signal will be generated as shown at Figure 5.20.

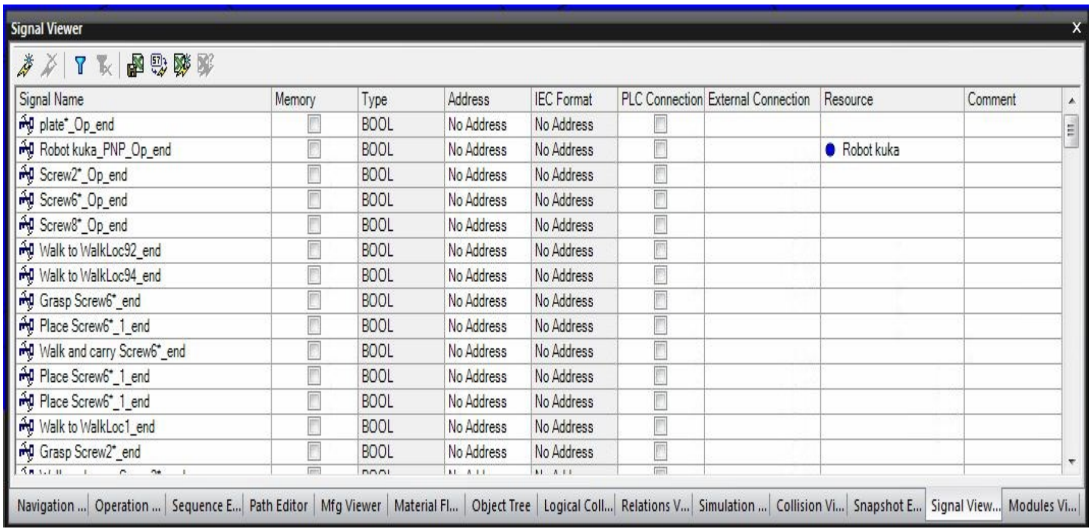


Figure 5.20. Schematic of signal viewer

However, signals for other devices will be generated using ‘Create Device Operations / Signals’ under signal generation option as shown at Figure 5.21. All the generated signals for devices and robot can be viewed actively in signal viewer table.

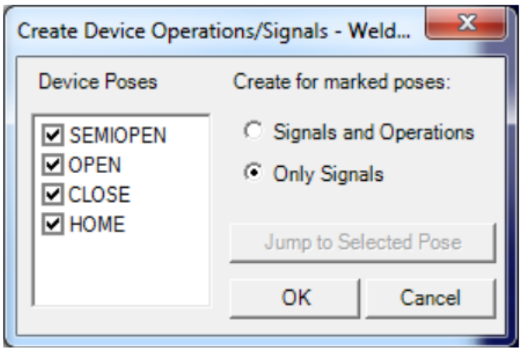


Figure 5.21. Signal generation

5.8.10. Logics definition in simulation

As mentioned before, the main difference between time-based and event-based simulations is that, during the robot operating, sequences of operations are defined and transferred to robot by using logic and signals. In event-based simulation logics should be used to control the operations' sequence; these logics determine whether the process in each step starts or not.

Three different solutions of logics are available in Process Simulate as following:

- **Sequence transition**

  This type of logic is used when devices and operations cannot be associated or controlled by PLC (Programmable Logic Controller) device; the practical example of this logic is when the operator performance should be controlled

- **Logic block**

  Logic block can control robots and other operations during the process.

- **Module**

  The modulus controls devices which are connected to the PLC. These devices including robot and devices which have PLC connections.

In this thesis during the event-based simulation transitions and modules have been used.

5.8.10.1. Transition

Transitions can be added to the simulation from the 'Sequence Editor' viewer; for example if a start button should be added to the operation for initiating the operation, the transition is provided in sequence editor. Transition logics are shown in Figure 5.22.

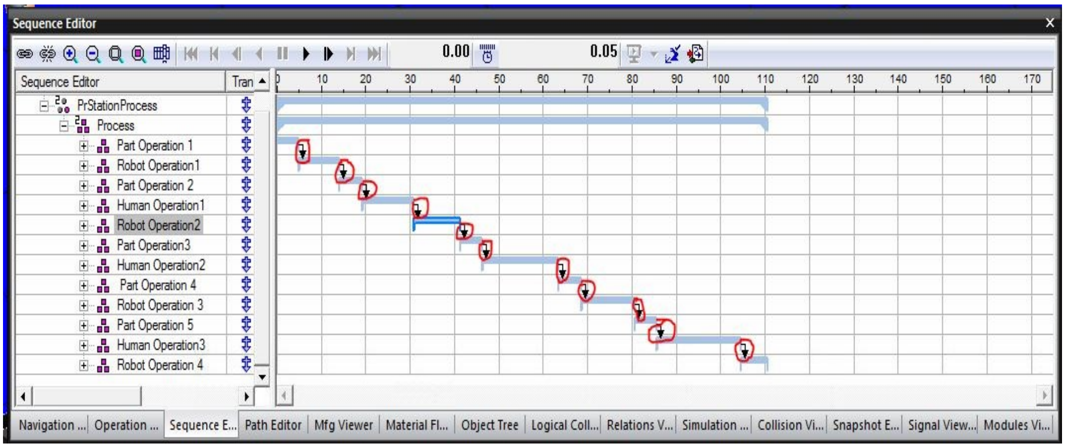


Figure 5.22. Transitions in sequence editor

With reference to the above diagram input the following common conditions for each transition as per steps 4-7.

5.8.10.2. Module

Module is a logic option in which signals are presented in a logical expressions format. These logics are used to control the overall operation of the procedure. In order to create Modules, the 'Module Editor' contains of logical expressions needs to be defined as shown at Figure 5.23.

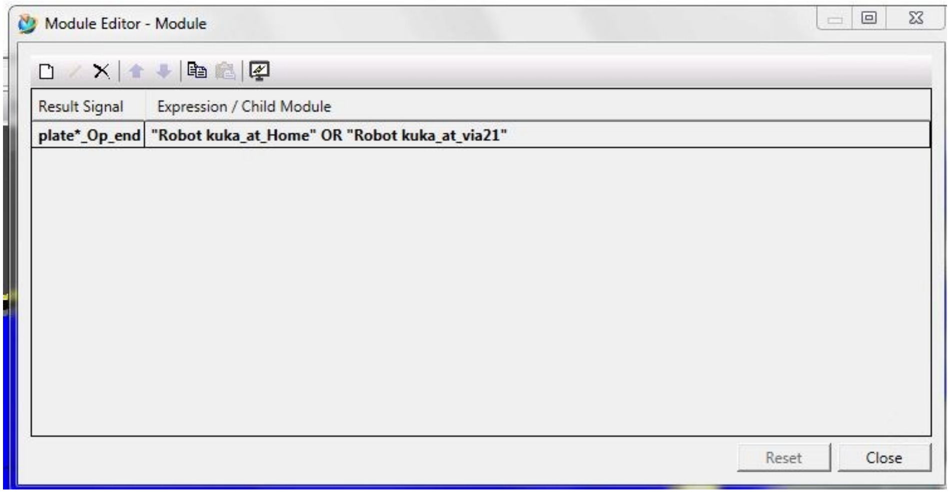


Figure 5.23. Module logic generation

5.8.11. Adding safety mat to the simulation

'Safety Mat' can be used in simulation to presented more realistic condition. 'Safety Mat' is a part of the available 'Smart Components' in Process Simulate that can be applied when the operator is the near distance of the fixture. These components have predefined logic block in themselves generating the required signals. These component can be produced in Process Simulate using Edit Logic Resource under CEE command as shown at Figure 5.24.

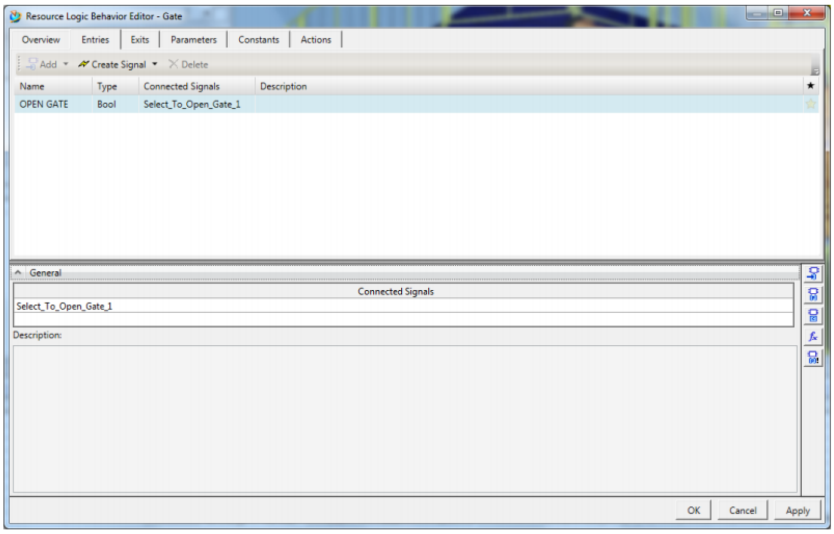


Figure 5.24. Definig safety mat in Process Saimulate

5.8.12. Adding emergency stop button to the simulation

In real operating condition, it is necessary to have an emergency stop button to enlarge the safety issues in the working cell. This emergency stop button is representative of a real button in working cell which would be pushed intentionally by the operator or would be activated automatically due to presence of the operator in working zone detected by sensors. During the simulation of the assembly process, the emergency stop button which is a part of 'Module' logic has to be defined. In this way, the 'emergency stop button' cab be defined using the 'Module Editor' command in Process Simulate as shown at Figure 5.25.

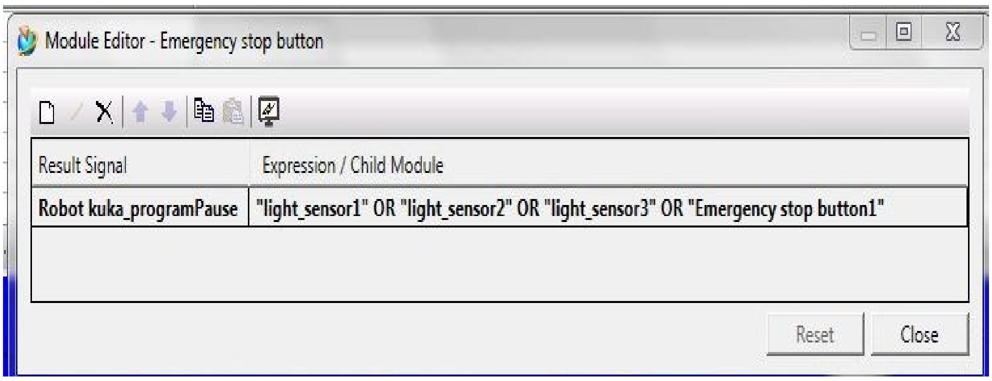


Figure 5.25. Definig emergency stop button in Process Saimulate

In this thesis, both sequence-based and event-based approaches—due to the application of a safety button and safety mat, which requires sensors in simulation—are used to model the manufacturing process. In Figure 5.26, the operation times needed for accomplishing tasks by the operator and robot in each step are shown. The total time resulting from the procedure simulation is 120 seconds. Figure 5.27 shows the collaborative environment between the human and robot, as well as the completed brake disc assembly.

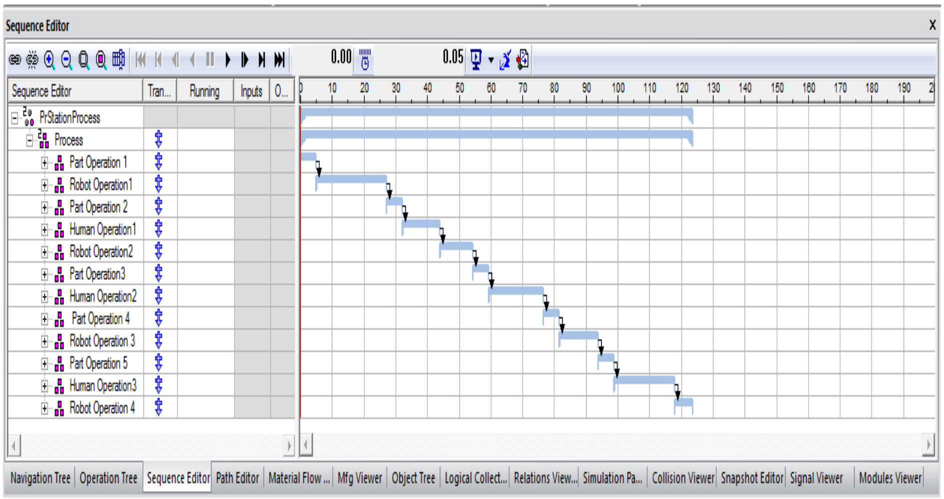
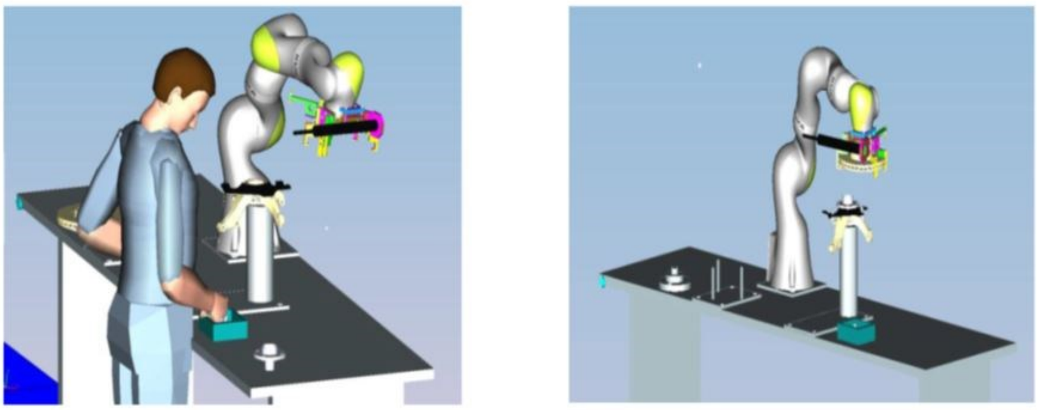


Figure 5.26. Gantt chart of operations during assembly



(a) Collaborative environment (b) brake disc assembly by the robot

Figure 5.27. (a) Collaborative environment; and (b) brake disc assembly by the robot

5.9. Evaluation and Discussion

Copying the manual assembly process of the brake disc, the primary operation sequence of the automated process was defined, as shown in Figure 5.28. As mentioned before, since each operator approximately assembles 160 brake discs in each day shift, it is obvious that they will undergo a very large workload (around 800 kg); this workload may cause serious ergonomic injuries, such as muscular pain for the operator, over a long period of time.

The use of the HTA method provides the possibility of combining human and robot tasks in a collaborative order, as shown in Figure 5.29. As mentioned before, three personnel were involved in this activity; one person for managing and consulting and the other two trained for the programming and running of the application. Tests were repeated five times during two weeks of working with the robotic prototype in laboratory conditions to gain a statistical basis.

As discussed previously, the main responsibilities of the assistant robot are picking and placing of the dust protection plate and the brake disc. In order to evaluate the feasibility of the hybrid assembly process proposed by the HTA method, few tasks were considered and the assembly process was modeled in a virtual environment. However applying stop button increased the total time but the safety of human was so important to prevent robots from harming humans. The total assembly process time based on the initial HTA diagram is 203 seconds. The HTA method facilitated the definition of tasks for operator and robot in a collaborative manner; however, some defects were observed during testing. It was observed that, when the operator intends to put the M8 screws on the brake disc in the last phase of assembly, the robot manipulator is partially obstructing the operator's sight. This occurrence forced the operator to change his position regularly to complete the task properly. Two solutions have been proposed to solve this problem; the first one is to return the robot manipulator to its home position, and the second one involves the use of the impedance control of the robot and hand-guided method (HG).

Although it seems that the first solution would be a perfect one, it is quite costly. Imagine that each time the robot manipulator has to come back to its home position and again return to the previous position for the screwing and tightening operation; this will be very time-consuming and thus reduce productivity. However, based on the second method, the hand-guided method, the robot is allowed to move only in predefined directions determined by the operator.

The robot was moved by the operator to the non-disturbing position and the operator put the screws on the brake disc. Regarding to abovementioned description and the hand-guided method as an extra task, the final collaborative tasks were redefined and the modified task sequences are presented in Figure 5.30. The schematic of collaborative work environment in laboratory is shown in Figure 5.31. It is worth mentioning that adding the hand-guided method increased the total processing time to 210 seconds.

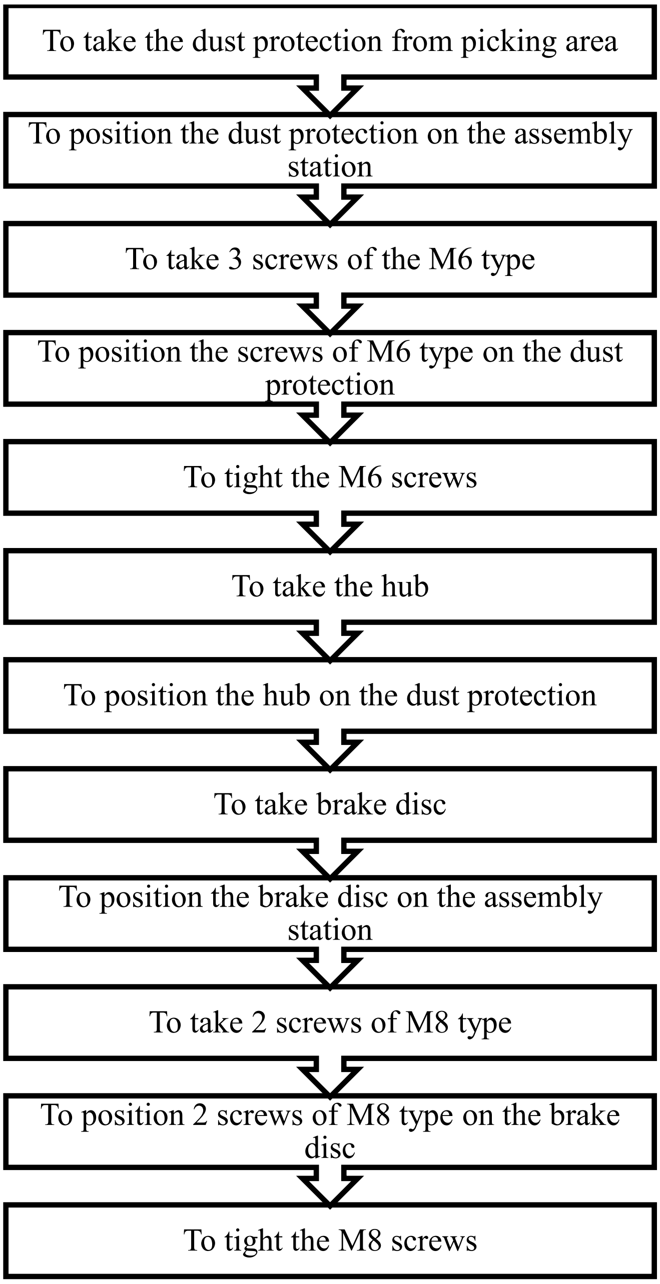


Figure 5.28. The initial assembly operation sequence.

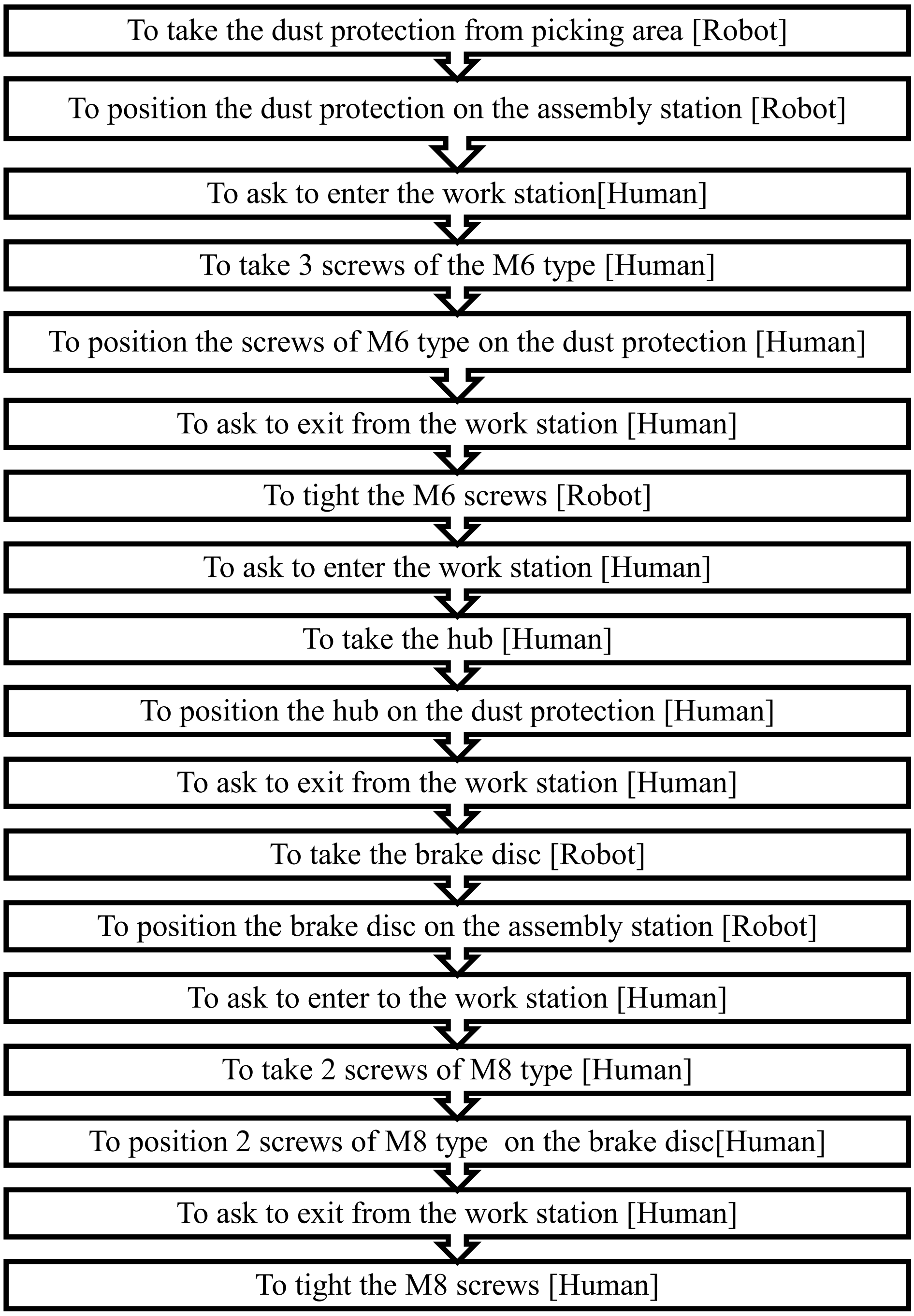


Figure 5.29. Modified assembly operation sequence with a robot.

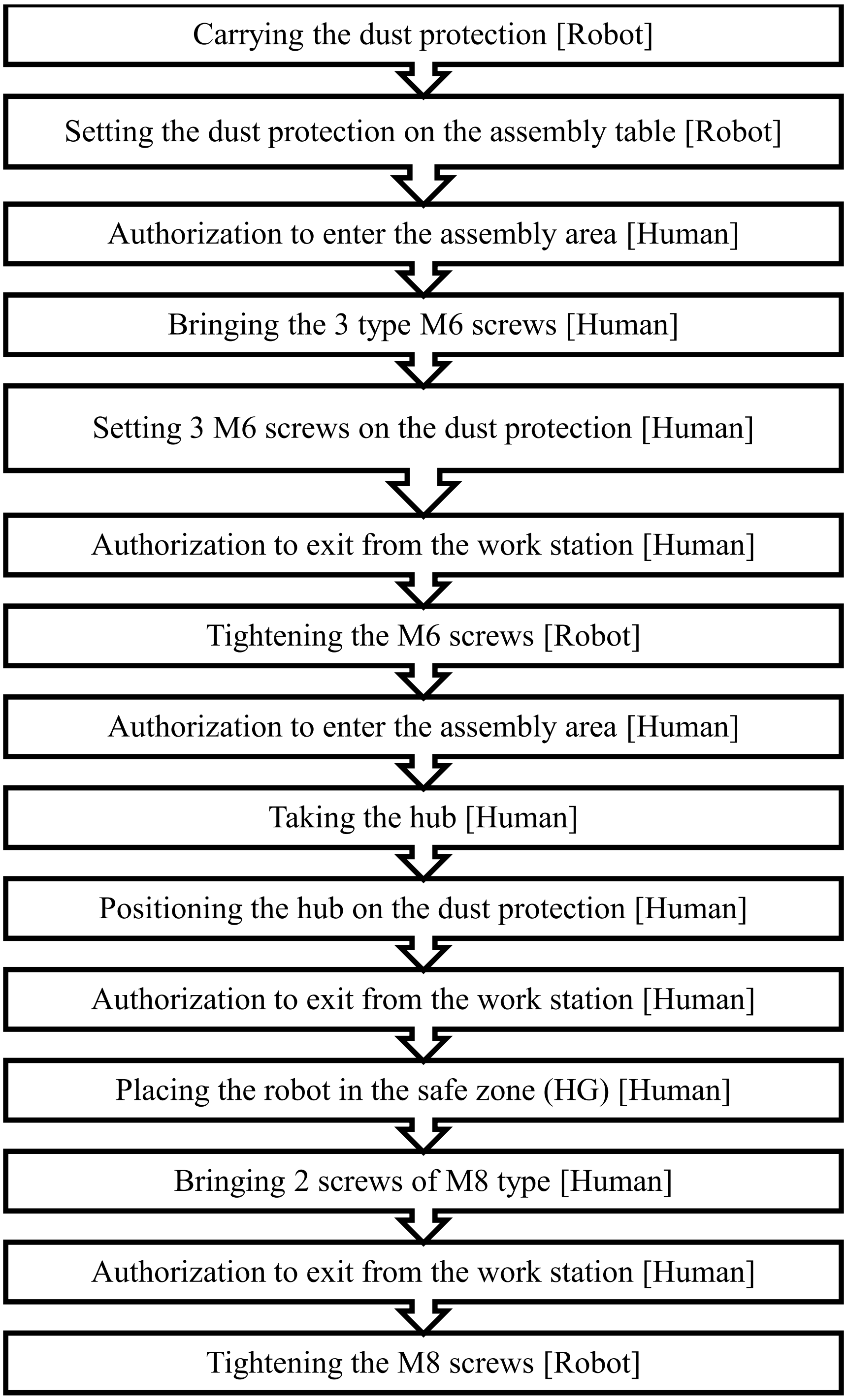


Figure 30. Human-robot collaborative task allocation with HTA.

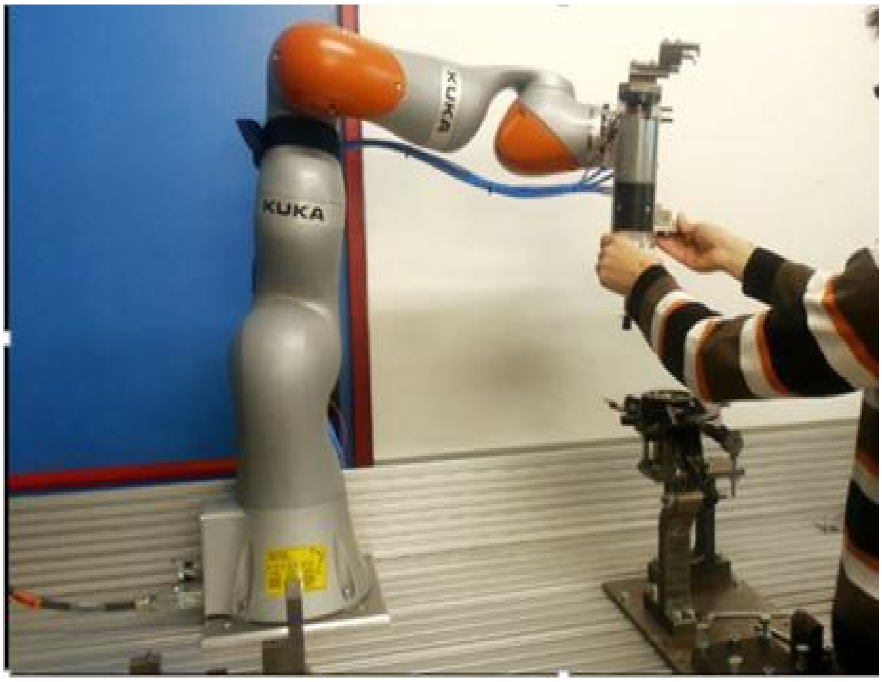


Figure 5.31. Human-robot collaboration with the hand-guided (HG) method during the assembly process of a brake disc.

5.10. Conclusions

In this chapter, the feasibility of human-robot collaboration was investigated for a case study (assembly of a brake disc) in experimental and simulation scenarios. In the first step, the AHP method was applied to prove the general advantage of the human-robot collaboration over the manual assembly solution. Productivity, quality, human fatigue, and safety were considered as the base criteria for the comparison of the possible different solutions while applying the AHP method. Using the HTA method, the primary algorithm for allocating the collaborative tasks to humans and robots was constituted. In the third step, the assembly process was simulated using the Tecnomatix Process Simulate virtual environment software to test the effectiveness of the HTA method in the case of task allocation. In order to obtain realistic results, the gripper that had been designed for the particular considered application was fully modeled and the complete procedure of the simulation has been described. Finally, the feasibility of the design was tested using the laboratory environment and defects were recorded. It was observed that, during the assembly, the robot manipulator obstructed the operator's sight, preventing them from completing the assembly properly. The hand-guided method was used to solve this problem based on the available standards in human-robot collaboration. According to the manual assembly process, every day each operator should work 8 hours in one shift, each brake disc weighs around 5 kg, and the assembly of one brake disc takes around 3 minutes. Considering the operator work shift hours and the brake disc assembly period, the operator should assemble approximately 160 brake discs and lift 800 kg throughout each working day. Considering at least 200 working days in a year, he should lift around 160,000 kg; in other words, he will undergo to a load of 1600 kN. This workload in a year could affect the operator fatigue accumulation, tiredness, and may cause serious injuries to the operator's muscles. This situation can also influence productivity and quality, because sometimes the operator is tired or has some pain in his muscles; this can cause the inappropriate insertion of the brake disc on the dust protection plate or the insufficient tightening of screws. These will cause a faulty assembly and decrease the quality and productivity. Although the collaborative procedure increases the total assembly time during experimental tests in laboratory environment (210 seconds) in comparison with the manual procedure in production line (180 seconds), operator ergonomics are improved and the risk of injury is considerably reduced.

Part of the work described in this chapter has been published in "Safety Design and Development of a Human-Robot Collaboration Assembly Process in the Automotive Industry, 2018 [46]" and "Human-Robot Collaboration Application in Automotive Industry: Brake Disc Assembly, 2018 [47]".

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Chapter 6

Case study 2: Developing the Human-Robot collaboration system based on speed and separation monitoring method (SSM)

6.1. Introduction

In production line, many tasks have repetitive nature such as welding, painting, and handling heavy and fragile objects. The idea of human-robot collaboration is to fill the gap between the manually and fully automated processes. Collaborative robots, as mentioned before, can be a solution to help an operator while performing the un-complex repetitive tasks. Robots can help the operator to share tasks and increase productivity which can lead to improvement of efficient and safe performance [1]. Human-robot collaboration in the same time and space has many hazards and risks related to operator safety. For this purpose, Occupational health and safety organizations rely on national and international standards to provide guidance for maintaining safety in the working environment. The International Organization for Standardization (ISO) Technical Specification (TS) 15066 has listed four different scenarios for increasing safety with industrial collaborative robot [2].

1. SMS: the first method is safety-rated, monitored stop method that requires a software or device to pause the function of robot when the worker is coming closer to the robot in order to prevent dangerous motion.

2. HG: The second is hand guiding method moving robot system by hand-operated device to transmit motion commands.

3. SSM: The third method is speed and separation monitoring which is increasing safety by specifying the minimum protective distance between a robot and an operator in the collaboration work space.

4. PFL: The fourth method is called power force limiting, it allows the contact between on operator and a robot, but the requirement is the control of robot momentum to avoid any injury and pain.

Recently, virtual environment plays an important role in designing various facility of production lines by providing analysis of difficult visualized situation. The implementation of virtual environment helps to reduce the risk of changing the production planning when unexpected dangerous situations are detected; also, it can help to improve cost, process time and process ergonomic safety [3].

The authors of [4] focused on the third method from ISO (TS) to investigate a set of metrics for SSM algorithm and to discover the collision avoidance path based on consideration of safety criteria, sensor uncertainty and variable control factors in robots. The aim of the research activity described in [5] is to present a new method for designing and optimizing hybrid reconfigurable systems. The reconfigurability is addressed by a clear task decomposition between robots and operators. Virtual environment simulation has been used to consider different scenarios of reconfigurability in working station to enhance the operator awareness and reduce the risk of injuries. In the research reported in [6] authors applied virtual environment to implement manufacturing tasks for building aerospace composite parts. This paper has two goals, one of them is short-term goal which is to enhance the behavior of human while collaborating with robot inside the virtual environment. The second goal is long-term goal, they investigated how to improve acceptability of Human-Robot collaboration (H-R-C) and to improve relevant collaborative conditions by means of virtual environment. The aim of the research reported in [7] is to obtain a collaborative procedure that results to be more fluent and acceptable for humans in case of teamwork with robot. The obtained results show an improved collaboration between human and robot and a reduction of stop-and-go command during collaboration. For this purpose, firstly they simulated the collaborative environment with robot and human then tested for confirmation in real world (laboratory environment). They use the virtual environment and train the operator how to behave with robot.

In previous chapter the first method of ISO 10218, Safety-rated monitored stop (SMS) during human robot collaboration for brake disc assembly was studied. In this chapter, the same case study as in chapter 5 is studied but based on another ISO standard in a virtual environment. After the operation tasks are decomposed and allocated to human and robot based on HTA method in a collaborative work place, SSM system using the virtual environment simulation code (Tecnomatix Process Simulate) is applied to determine the range for the minimum separation distance of human and robot in the brake disc assembly work station.

6.2. Task analysis in a collaborative workspace

In order to apply SSM method during collaboration is necessary to define tasks and duties between robot manipulator and operator. Since the methodology for performing Hierarchical Task Analysis (HTA) has been described in detail in chapter 5, we ignore to discuss the task analysis procedure again. The overall objective of this analysis to check the efficiency of the SSM method in this collaborative environment; the updated operator and robot tasks regarding to satisfying of the SSM method regulation and standards are allocated as in Table 6.1 and 6.2 respectively.

Table 6.1. Task definition and work sequences for operator

Role	Operator	
Purpose	Insert hub and change the robot tool tips	
Sequence	Task	Description
1	Ask to enter the work station	Operator pushes the access button and enters the work station
2	Take 3 screws type of M6	Take 3 screws M6 from the screw kit from picking area
3	Position screws of M6 type on the dust protection	Insert 3 screws M6 on the dust protection in assembly area
4	Change tip1	Position the tip1 on the tip kit
5	Take tip2	Take the tip2 from the tip kit
6	Position the tip2 on the gripper	Insert on the gripper
7	Take the hub	Take the hub from hub kit
8	Position hub on the dust protection	Insert hub on the dust protection in assembly area
9	Take 2 screws type of M8	Take 2 screws M8 from the screw kit from picking area
10	Position 2 screws type of M8 type on the brake disc	Insert 2 screws M8 on the brake disc in the assembly area
11	Ask to exit from the work station	Operator pushes the access button and exits the work station

12	Enter to the workstation without asking	Operator enters to the workstation and walks around robot in order to test sensors and verify SSM method efficiency

Table 6.2. Task definitions and work sequences for robot manipulator

Role	Robot Manipulator	
Purpose	Assemble the brake disc on the assembly station	
Sequence	Task	Description
1	Take the dust protection	Take the dust protection plate from the plate kit from picking area
2	Position the dust protection on the assembly station	Insert dust protection on the semi-finished part which is received from previous station
3	Go back to the home position	After finish the task, the robot comes back to home position
4	Prepare for screwing	Go to the assembly station
5	Tight of the M6 screws	Tightening the three screws of M6 type
6	Take the brake disc	Take the brake disc from brake disc kit from picking area
7	Position the brake disc on the assembly station	Insert the brake disc on assembly station
8	Tightening of the M8 screws	Go to the assembly area and do tights the two screws type of M8
9	Change the speed otherwise stop	When human enters in the workstation without pushing button, the sensors alarm the robot to reduce speed or stop until the safe distance is provided.

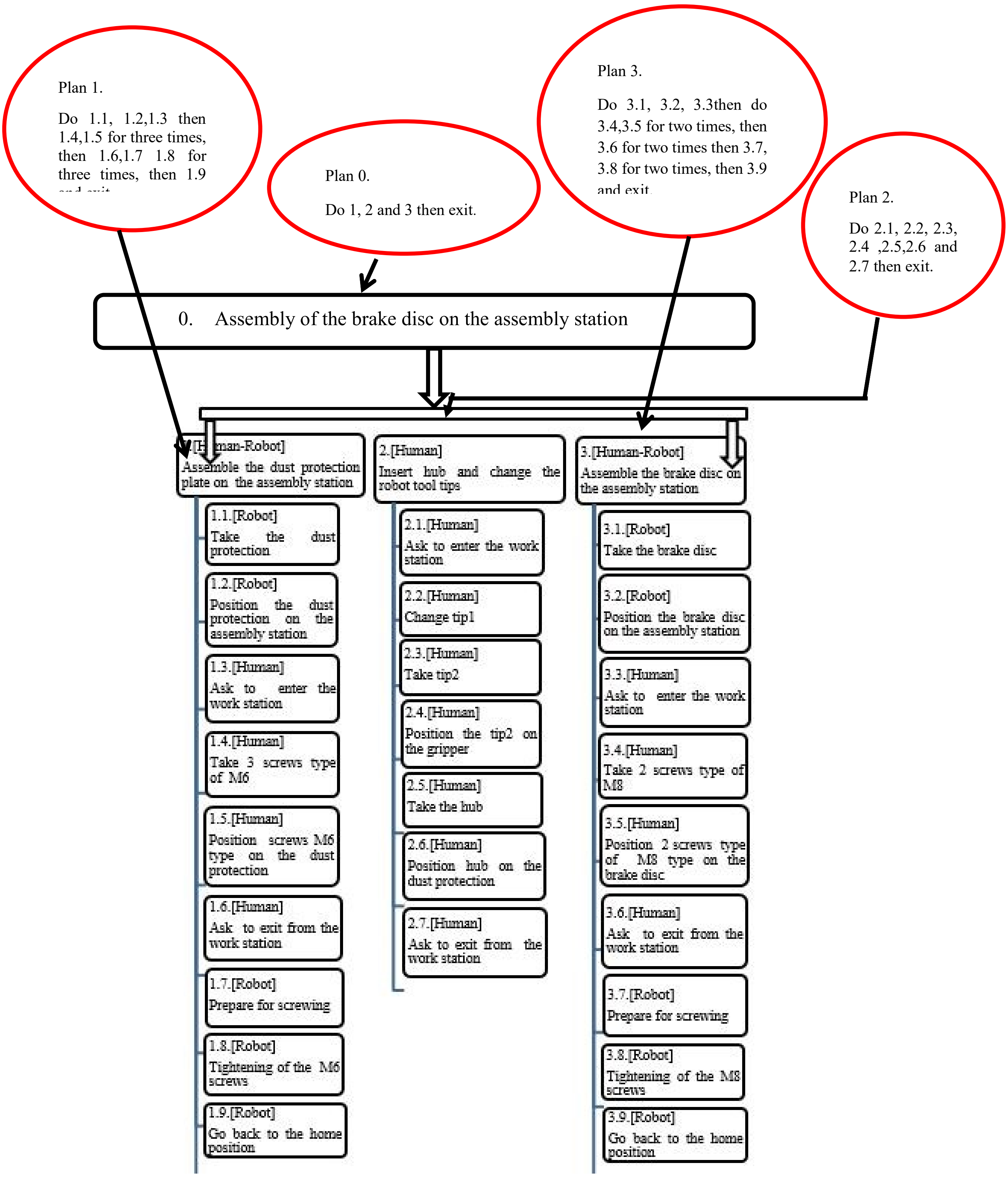


Figure 6.1. Hierarchical diagram of brake disc assembly

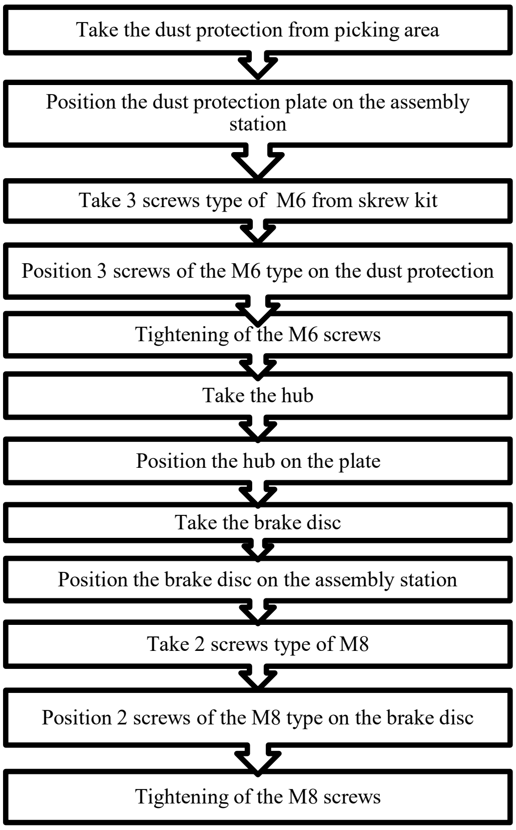


Figure 6.2. The initial assembly operation sequence

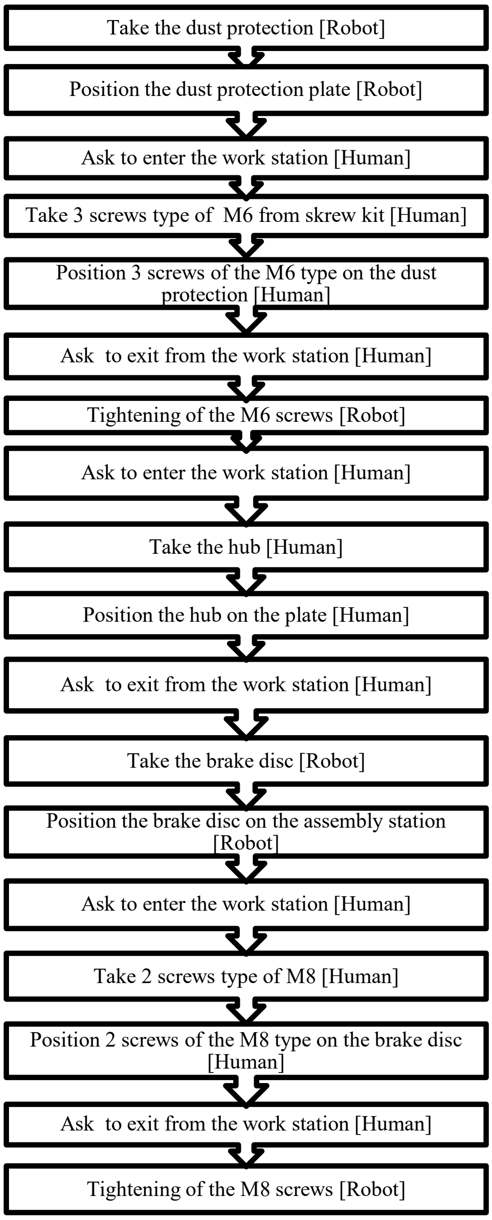


Figure 6.3. Modified assembly operation sequence with a robot.

6.3. Simulation procedure

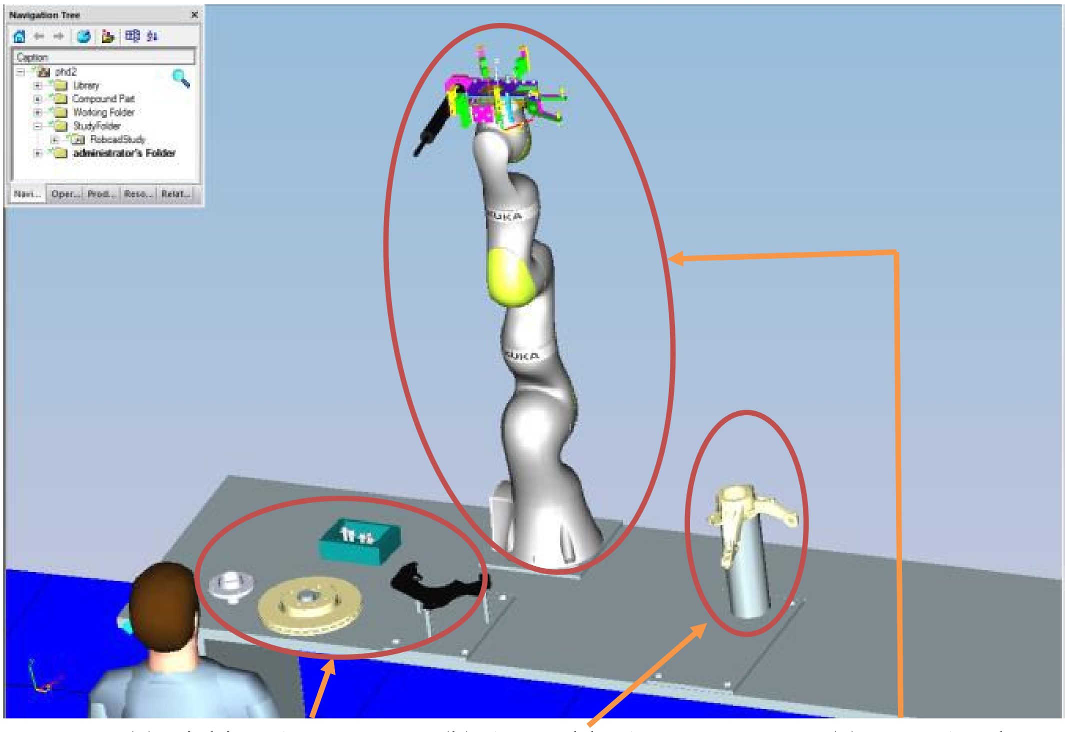
In the production line, the assembly of brake disk is performed in several steps. The objective is to reproduce a workbench assembly in one cell, at a laboratory scale, where the human-robot collaboration is introduced. It should be clear that when a human operator and a robot are working together in the same work place, the risk of collision between them is high if not appropriately controlled. In any case is higher with respect to the usual organization where human operator and robot are not working together in the same work place. Therefore, these models allow us to make experience of this relatively new manufacturing environment and further to develop some optimization. The assembly area in the virtual environment is divided in two main parts as shown in Fig 6.4.

(a) Picking area: the zone of the workbench in which the robot picks up the various components for the assembly.

(b) Assembly Area: where the upright and bearing are placed and fixed to allow the assembly.

The components to be assembled are placed on the workbench to supply what is needed to perform the assembly tasks and the appropriate tools for the operator. The components located on the workbench consist of the screw kits, the hub kit, the dust protection kit, the brake disc kit and the tip kits.

In order to develop a solution that is acceptable for this human-robot collaboration procedure, which has always a high risk of risk of collision, a kuka robot has been considered in this research. Complete characteristics of the Kuka lbr iiwa robot have been described in previous chapters. Importantly in the collision avoidance perspective, this robot has a quick response in the case of dangerous situations. The Kuka (LBR IIWA R820 14") robot, as illustrated in Fig.1 (c), is used. This robot is characterized by a maximum range of 820 mm and a payload of 14 kg. It is located in front of the workbench. This robot has precise system of sensors placed on each axis.



(a) Picking Area (b) Assembly Area (c) KUKA robot

Figure 6.4. Workbench area

The aim of applying H-R-C in this procedure is to help the human operator by applying a robot for improving the ergonomic by reducing the workload. This aim is relevant since the part weight is high and might cause muscular pain after repetitive tasks. As mentioned in previous chapter, Due to the fact that, during the manual assembly of brake disc, each operator should lift 5 kg brake disc and each operator works 8 hours in one shift, and during this time he assembles around 160 brake discs, at the end of the day he results to have lift more than 800 kg. The components of the break disc modeled in virtual environment is shown at Figure 6.5. Using H-R-C will reduce considerably the burden lifted by an operator, since the heavy loads are now managed by the robot.

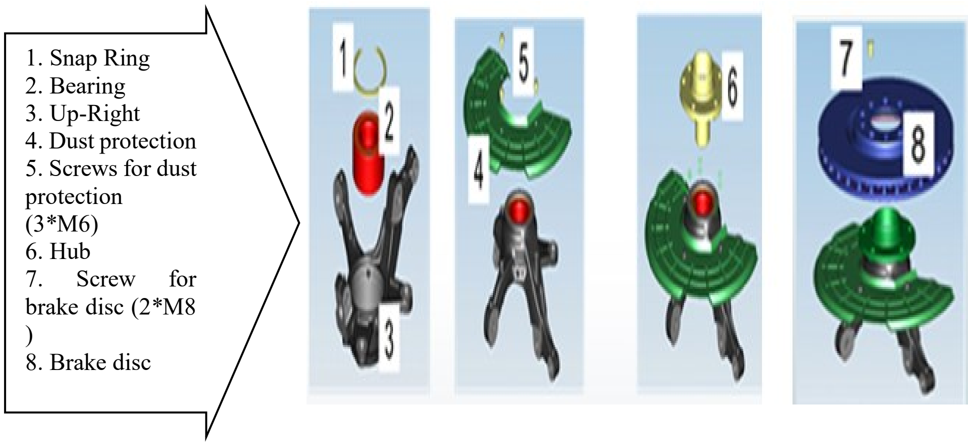


Figure 6.5. CAD parts of brake disc

Tasks have been allocated to human and robot as following: The assembly job is started with taking the dust protection from picking area by robot and inserting it on the upright and bearing on the assembly area. Then the 3 M6 screws are taken from the screw kit in picking area by the operator and are tightened on the plate by the robot. In the third step, hub is taken from picking area by the operator then inserted on the dust protection. In the fourth step, the brake disc is picked from picking area and inserted on the hub in the assembly area by the robot. In the last step 2 screws are taken by the operator from screw kit then the robot tights on the brake disc in the assembly area. It is also important to mention that, safety cameras are placed in workstation to detect any kind of human and robot motions during their interactions in order to test sensors to calculate parameters of speed and separation monitoring method.

6.4. Speed and Separation Monitoring method (SSM)

This chapter focuses on the third human-robot collaborative scenario: “speed and separation monitoring” (SSM). In order to preserve a static safe separation distance between the robot and a human walking around the collaborative workspace, the SSM method offers a reasonable solution. The purpose of this method is to measure continuously the separation distance between the robot and the operator and compare with the so called authorized (worker protective) distance. Using the SSM method when the separation distance tends to reduce below the authorized distance, the robot stops any kind of motion. The robot initiates again its movement when the separation distance becomes equal or greater than the authorized distance [2, 8]. SSM can offer reasonable solutions in order to preserve a safe separation distance between the robot and a human walking around the collaborative workspace. SSM can be implemented both under static and dynamic conditions. The Static SSM method considers constant the human and the robot speeds. While the dynamic SSM method can consider variable speeds. In this research, the static SSM method has been used to reduce potential risks in human-robot collaboration. The equation for calculating the minimum protective distance in human-robot collaboration in ISO/TS 15066 [2] is the extended version of the one which is defined in ISO 13855 [10] for determining the protective distance for immobile machines.

According to the ISO/TS15066 [2], the minimum protective distance, (S), at time (t_0) is given by equation (1).

$$S(t_0) \geq \left(\int_{\tau=t_0}^{\tau=t_0+T_R+T_S} v_H(\tau)dt \right) + \left(\int_{\tau=t_0}^{\tau=t_0+T_R} v_R(\tau)dt \right) + \left(\int_{\tau=t_0+t_R}^{\tau=t_0+T_R+T_S} v_S(\tau)dt \right) + (C + Z_S + Z_R) \quad \textit{Eq. 1}$$

Where (V_R) is speed of the robot in the direction of the human, (V_H) is the directed speed of human in the collaborative workspace in the direction of the moving part of the robot, (V_S) is the speed of robot in the stopping path, from activation of the stop command until the robot has stopped. (T_S) is the time to stop the robot motion. (T_R) is the robot responding time in case of the operator presence. Where the part of body can intrude into the sensing area before it is detected, the uncertainty disturbance of boundary distance to exception of operator reach is (C). The uncertainty of robot position and operator position (sensor) are respectively (Z_R) and (Z_S) [2, 8].

It is important to mention that, V_R is the robot gripper velocity and (V_H) is the manikin center velocity. The SSM stopping diagram is presented in Fig 3. The total time for stopping the motion of the robot is the summation of the sensor detection time (t_d), the robot reaction time (t_r) and the robot stopping time (t_s). The hazard area is therefore representative of the authorized stopping distance. As soon as the authorized stopping distance is calculated, a stop signal will be sent to the robot control system [10].

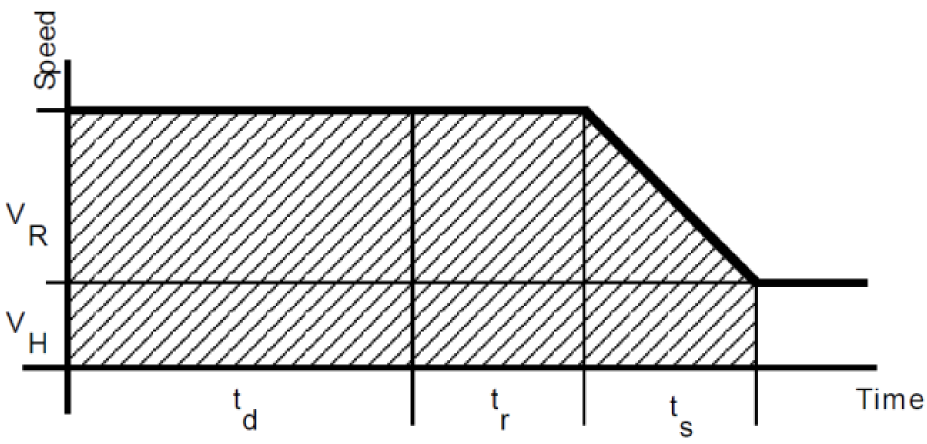


Figure 6.6. SSM Stopping Diagram [9].

6.5. Results and discussion

As mentioned in chapter 5, Tecnomatix Process Simulate software is used to simulate the assembly process of the brake disc. Since during the human-robot collaboration based on SSM system it is necessary to define sensors and logics to construct the operations sequence, in this chapter only event-based method is used to model the advanced collaborative workspace as shown at Figure6.7.

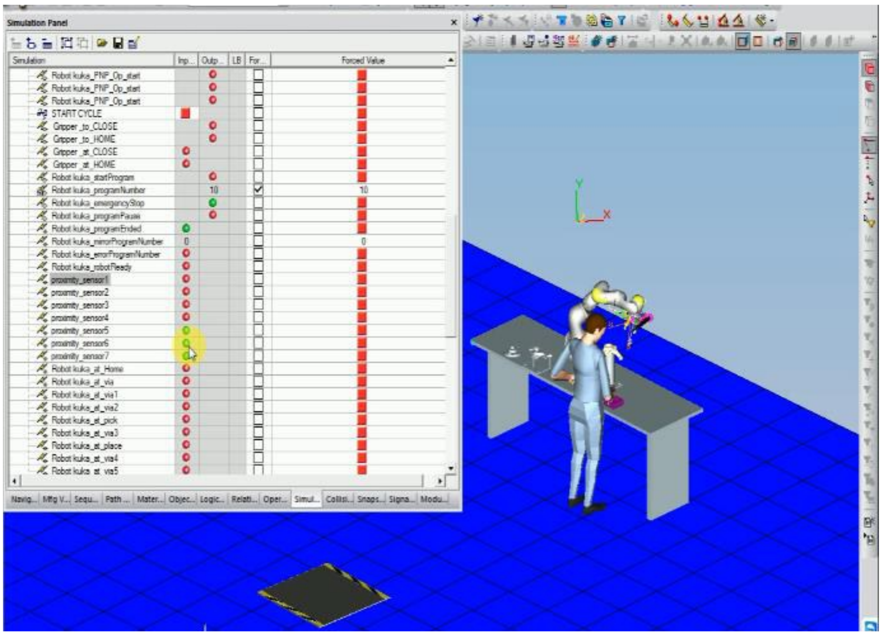


Figure 6.7. Virtual environment in event-based mode

Equation (2), which is a linearized form of the equation (1), has been used to calculate the minimum allowable robot-human distance under static condition [8, 10].

$$S= (V_H T_R + V_H T_S) + (V_R T_R) + B + C \qquad \text{Eq. 2}$$

In order to calculate the minimum separation distance, all the necessary factors should be determined. The human speed (V_H) is variable between 1600 mm/s to 2000 mm/s., In order to be on the safer side, the worst-case value of human speed (V_H = 2000 mm/s) is selected based on ISO/TS 13855 [10] and the maximum velocity of Kuka robot (V_R= 250mm/s) is considered. The term (B) which is the robot stopping distance and the term (T_S) are calculated based on equations (3) and (4) respectively mentioned in ISO 10218-1 [11] as following:

$$B = V_R^2 \ / 2a \qquad \text{Eq. 3}$$

$$T_s = V_R \, / \, a \qquad \text{Eq. 4}$$

In the equations (3) and (4), (a) is the worst-case deceleration value of the robot during the stopping procedure.

While equations (2)-(4) seem to be simple, a quite complex procedure should be done to determine these values. The two parameters (T_R) and (a) should be determined through the simulation procedure and the formula presented by [2]. According to [8] the stopped position of the robot ($P_{s,i}$), which is the summation of robot distance traveled while the sensors are detecting plus the distance traveled while the robot stopping begins, is calculated for different percentages (i%) of robot maximum velocity (V_R) as following :

$(i = \%V_{R,100})$

$$P_{s,i} = (V_{R,100}\, T_R + V_{R,100}^2 / 2a + P_{s,100}) - (V_{R,100}\, T_R)i - (V_{R,100}^2 / 2a)\, i^2 \qquad Eq.\ 5$$

$C_0 = (V_{R,100}\, T_R + V_{R,100}^2 / 2a + P_{s,100})$
$C_1 = (V_{R,100}\, T_R)$
$C_2 = (V_{R,100}^2 / 2a)$

Having determined the stopping position of robot regarding to different percentages of robot maximum speed through the simulation, it is possible to implement the regression analysis in equation (5) to determine the values of the variables of (T_R) and (a) as presented at Figure 6.8 and Table 6.3. Then the robot stopping distance and stopping time (T_S) can be easily calculated based on equation (3) and (4). However, to calculate (C), which is the summation of robot and human position uncertainty and intrusion distance safety margin for separation, is a quite challenging process. One way to calculate (C) based on ISO 13855 [10] is throughout consideration of the worst-case scenario, which is implemented in this research following what reported in [3,9].

Table 6.3. Parameters of robot data

Speed (mm/s)	$i = \%V_{R,100}$	$P_{s,i}$ (mm)
0	0	0
125	5	10.7
250	10	23.5
375	15	39.2
500	20	54.1
625	25	78.9
750	30	138.3
950	38	212.1

1250	50	297.6
1575	63	396.1
1875	75	498.2
2200	88	624.1
2375	95	702.6
2500	100	774.3

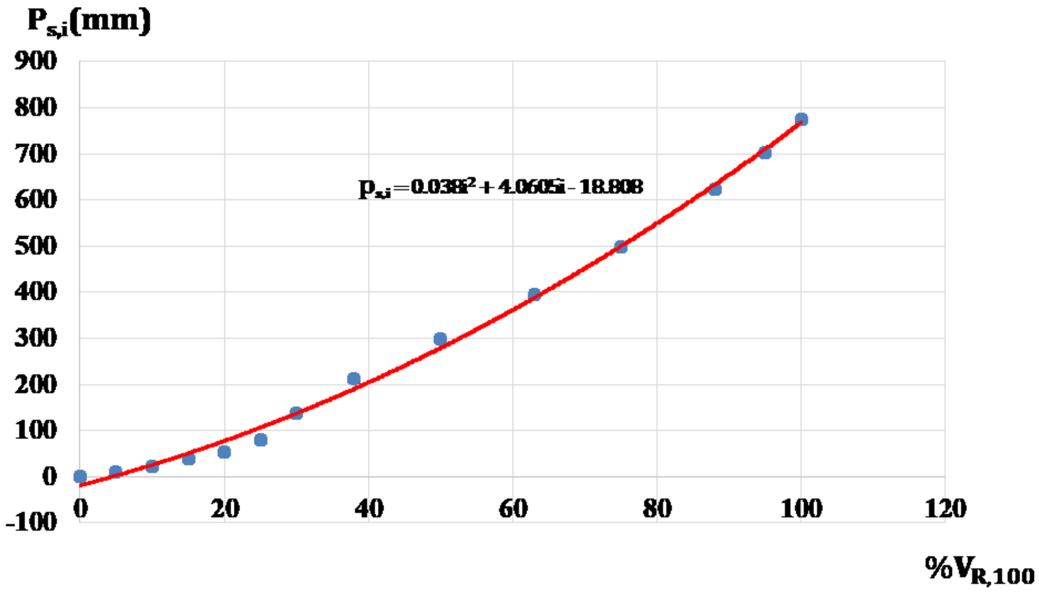


Figure 6.8. Stopping position of robot regarding to different percentages of robot maximum speed

As shown in Figure 6.8, by equalling the curve's equation constants to C_0, C_1 and C_2 , the robot reaction time (T_R) and the robot acceleration (a) are calculated. According to the above-mentioned description, the parameters of equation (2) are determined as in Table 6.4 and Figure 6.9. The minimum separation distances are calculated based on the respective robot velocities as below:

C= 850 + d ⇨ d is the extra buffer depends on the precision of the monitoring sensors

Based on the equation 2: $S = (V_H T_R + V_H T_S) + (V_R T_R) + B + C \quad Eq(2)$

If $25\ mm/s < V_R < 2500\ mm/s$ *Then* $1.23\ m \leq |S| \leq 2.04\ m$

Table 6.4. Distance variable based on percentage of maximum speed.

Speed (mm/s)	Distance (m)
0	0
25	1.23
50	1.46
125	1.61
250	1.648
375	1.672
500	1.706
625	1.735
750	1.768
950	1.799
1250	1.828
1575	1.852
1875	1.893
2200	1.924
2375	1.982
2500	2.04

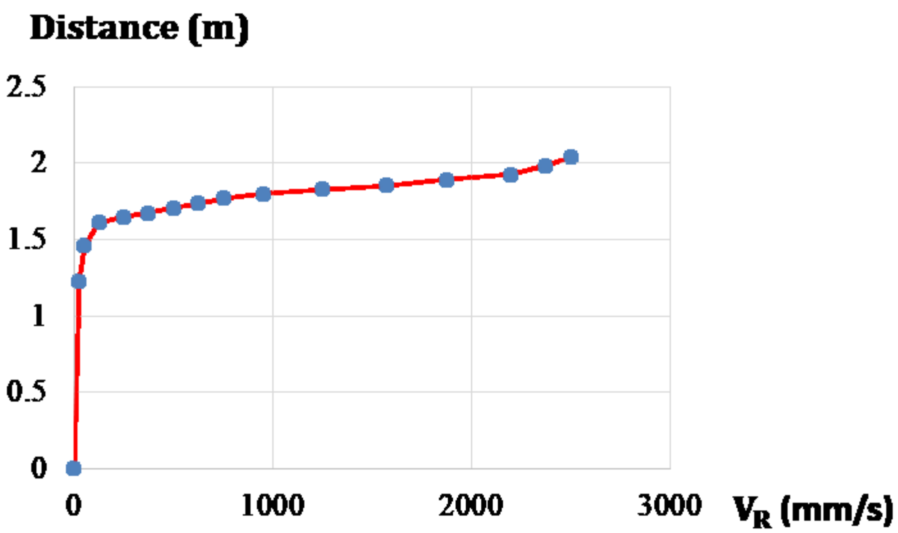


Figure 6.9. Distance variable based on percentage of maximum speed.

The schematic of human-robot interaction in the assembly cell is shown in the Figure 6.10.

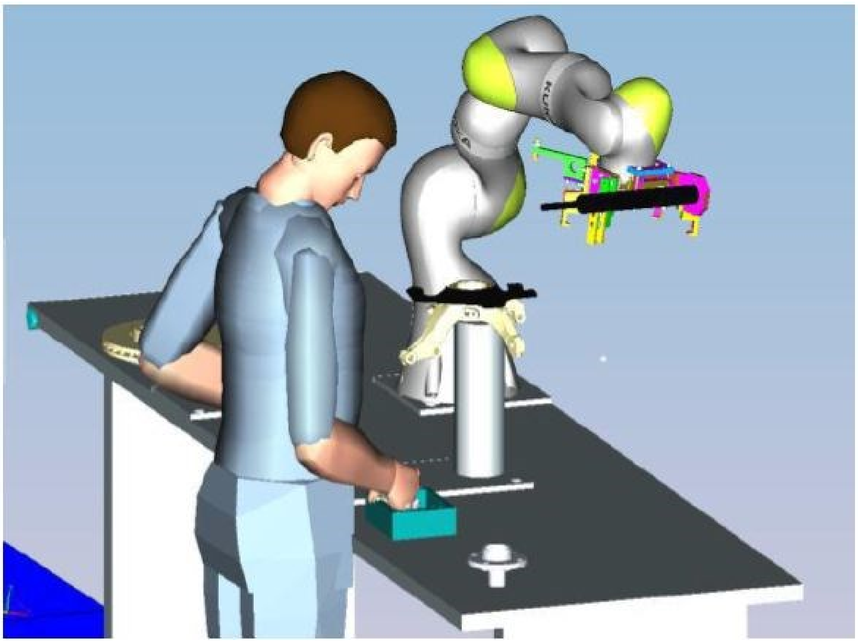


Figure 6.10. Human-Robot collaboration in assembly cell

Sensors in the working area calculate the distance (D) between the robot and any moving or movable object all the time as soon as (D) becomes less than the minimum separation distance (S). Sensors will issue a stop signal to the robot and the robot stops any kind of motion as shown in Figs 6.11 and 6.12.; again, when (D) becomes larger than the minimum authorized distance the robot begins to work.

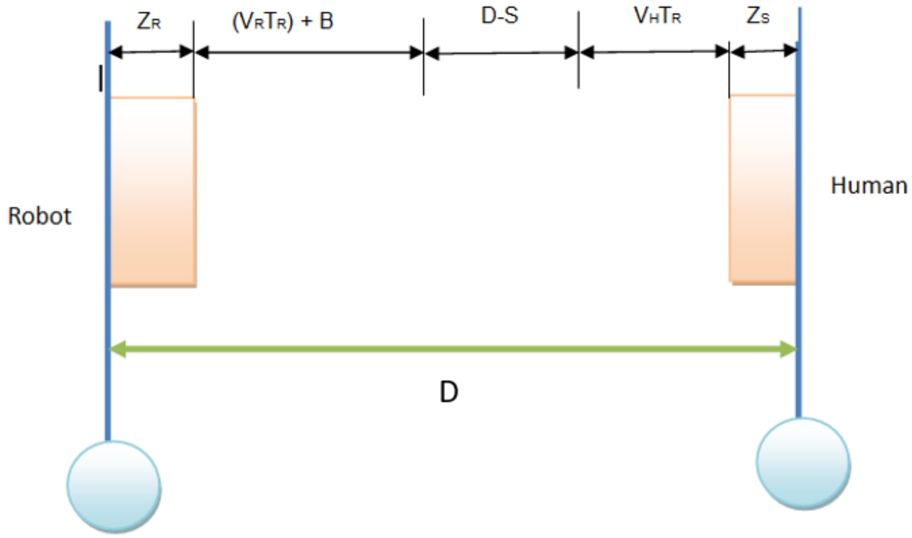


Figure 6.11. The SSM issues a stop when (D – S) < 0 [10]

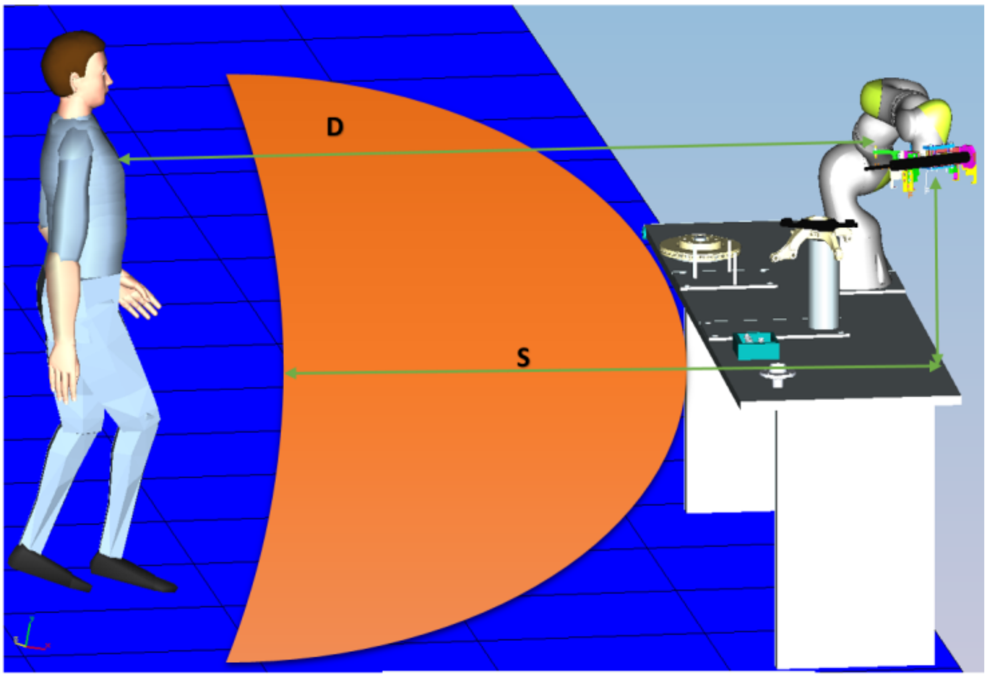


Figure 6.12. Human-Robot collaboration with SSM method

6.6. Conclusions

In this chapter, SSM system, as one of the available evaluation procedure in ISO/TS 15066, has been applied to increase safety in assembly cell using human-robot collaboration.

One of the relevant point for worker safety, when he is working in the same workplace of the robot, is to assure in any circumstances that the minimum separation distance is maintained.

According to the ISO/TS 15066, a linearized formula has been used to determine the minimum separation distance between the robot and human in assembly work station. In order to determine the parameters of this equation, it is necessary to estimate the robot stopping distance (B), robot stopping time (T_S) and human-robot position uncertainties (C), however calculating the robot reaction time (T_S) and the respective robot acceleration (a) is a quite complex procedure. A virtual environment tool has been used to simulate the assembly process through different percentages of robot maximum speed with respect to different stopping position of robot. In this way, the robot response time and acceleration have been calculated by equalling the curve's equation constants, obtained from the software, to the equation constants. The minimum allowable separation distances between human and robot have been estimated for different velocities of robot and the results were reported. As soon as the distance between the robot and human becomes less than the authorized separation distance, the robot stops working and when the distance returns to be larger than that the authorized one, again the robot begins to work. In second case study the minimum protective distance between human and robot was calculated.

In chapter 5,the achivment was improve operator ergonomics and increase productivity during collaboration by allocate tasks between human and robot. In chapter 6 beside improve ergonomic issues, the safty of othe operator during collaboration was increased by determining minimum safety distance between human and robot.

However always there is a need to use the most advanced sensors in the working area where human-robot cooperation takes place in order to reduce any risk of injuries.

Part of the work described in this chapter has been published in "Application of speed and separation monitoring method in human–robot collaboration: Industrial case study, 2017 [12]" and "Safety Design and Development of a Human-Robot Collaboration Assembly Process in the Automotive Industry, 2018 [13]" and "Human-Robot Collaboration Application in Automotive Industry: Brake Disc Assembly, 2018 [14]".

6.7. References

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Chapter 7

Conclusion

7.1. Overview of thesis

First chapter belongs to description of background, problem and overall objective of the thesis. In the second chapter, detailed description about safety standards and regulations of robots have been reviewed, then technical specifications related to four different scenarios for increasing safety of industrial collaborative robots were discussed. In the third chapter, the structure of Analytic Hierarchy Process (AHP) and Hierarchal Task Analysis (HTA) as decision making methods have been described. Constitution of a hierarchy task analysis for decomposing and allocating of tasks has been studied in detail. In chapter four, the detailed description of the thesis has been presented. This methodology flowchart helps to have a broad view about what has been done in this thesis. In chapters five and six, results of the analyses have been presented.

7.2. Results and findings

Analyses have been done for a case study (assembly of a brake disc) to evaluate the methodology for applying human-robot collaboration in the assembly line. Different scenarios of human-robot collaboration with respect to predefined colloborative standards and regulations have been modeled nad tested. The feasibility of the proposed approach has been evaluated in both experimental and virtual environments. The first part of the analyses has been devoted to evaluate the proposed methodology for applying human-robot collaboration system based on the safety standards and technical specification of SMS (Safety-rated Monitored Stop) and HG (Hand-Guiding) methods. In the first step, the AHP method was applied to prove the general advantage of the human-robot collaboration over the manual assembly solution. Productivity, quality, human fatigue, and safety were considered as the base criteria for the comparison of the possible different solutions while applying the AHP method. It has been approved that human-robot collaboration system has superiority over the manual-only system regarding to above-mentioned criteria. The primary algorithm for decomposing and allocating the collaborative tasks to humans and robots was constituted using HTA method. The collaborative tasks have been oriented for human and robot by task analysis. Tecnomatix Process Simulate has been used to model the virtual environment of the assembly cell for evaluating the effectiveness of the HTA algorithm. In order to obtain realistic results, the robot's gripper and sensors have been designed in virtual environment software for modeling the assembly of the brake disc and at end the feasibility of the design has been tested in the laboratory environment and defects were recorded.

It was observed that, during the testing of the assembly procedure, the robot manipulator obstructed the operator's sight, preventing them from completing the assembly properly. The hand-guided method (HG) has been used to solve this problem based on the available standards in human-robot collaboration. During the manual assembly process in factory, every day each operator should work 8 hours in one shift, each brake disc weighs around 5 kg, and the assembly of one brake disc takes around 3 minutes. This means that the operator should assemble around 160 brake discs and lift 800 kg throughout each working day. Considering at least 200 working days in a year, he should lift around 160,000 kg or in other words, he will undergo to a load of 1600 kN. This amount of workload not only could affect the operator fatigue accumulation, tiredness, and safety, but also could reduce the operator's concentration which will may result in inappropriate completing of the assembly. During the assembly of the brake disc in manual assembly line, it has been observed as the operator feels exhausted the brake disc has been positioned on the dust protection plate improperly or the screws not tightened appropriately. Although the collaborative procedure has increased the total assembly time (210 seconds) in comparison with the manual procedure (180 seconds); However, after the assembly cell has been improved using the virtual environment software and tested in the laboratory, operator ergonomics have improved and the risk of injury was considerably reduced. In other words, the operator does not need to be imposed on such a huge workload.

In the second part of thesis, SSM system, as the other evaluation procedure in ISO/TS 15066, has been applied to increase safety in the collaborative assembly. The main goal of this analysis was to assure in any circumstances that the minimum separation distance between human and robot is maintained. A formula based on ISO/TS 15066 has been used to determine the minimum separation distance between the robot and human in the assembly work station. In order to solve this equation, it is necessary to determine the robot stopping distance (B), robot stopping time (T_S) and human-robot position uncertainties (C), however calculating the robot reaction time (T_S) and the respective robot acceleration (a) is a quite complex procedure. The assembly cell has been modeled using Tecnomatix Process Simulate to find the stopping positions of robot with respect to different percentages of robot maximum speed. Based on the robot positions determined during the simulation, the equation of the robot position with respect to the robot velocity has been captured.

By equaling the curve's equation constants, obtained from the software, to the formula defined based on ISO/TS 15066, for determining the position of the robot, the robot reaction time and acceleration could be estimated. The minimum allowable separation distances between human and robot have been estimated for different velocities of robot and the results have been reported. It has been shown that, as soon as the distance between the robot and human becomes less than the authorized one, the robot stops working and when the distance returns to be larger than that the authorized distance, again the robot begins to work. It is suggested that to always use the sensors with the maximum accuracy to estimate the precise minimum separation distance between human and robot to reduce any risk of injuries.